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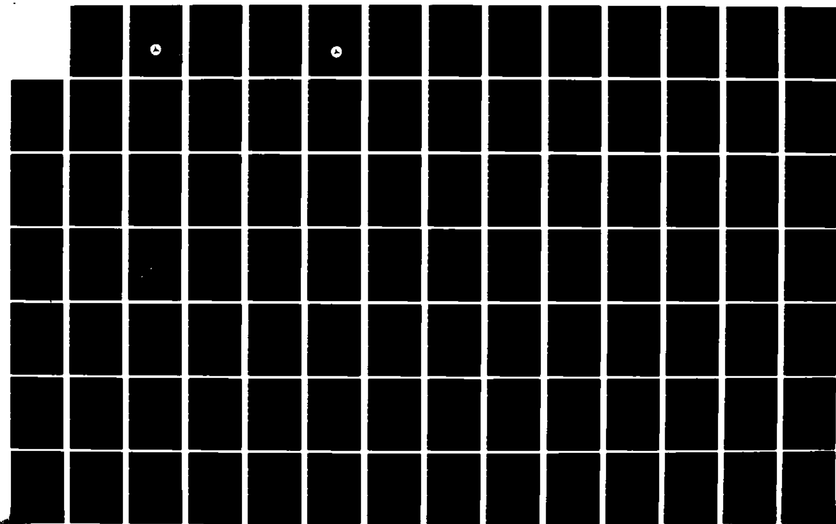

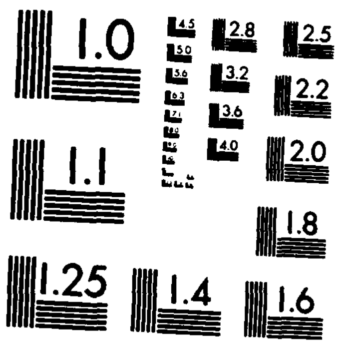

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CAORF 42-8009-02

CAORF TECHNICAL REPORT

SIMULATION EXPERIMENT

TUG USAGE FOR CONTROL AND DECELERATION IN RESTRICTED WATERWAYS

DEPARTMENT OF TRANSPORTATION

MARITIME ADMINISTRATION
OFFICE OF RESEARCH AND DEVELOPMENT

COMPUTER AIDED OPERATIONS RESEARCH FACILITY
NATIONAL MARITIME RESEARCH CENTER
KINGS POINT, NEW YORK 11024

DECEMBER 1982

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The investigations described in this report form the first part of a series of experiments planned at the Computer Aided Operations Research Facility (CAORF) to investigate the effectiveness of tugs in restricted waterways and the variability in pilot operating procedures. The present experiment involved comparisons between harbor pilots and docking masters, ship size (80,000 DWT and 250,000 DWT tankers), tug number, tug power, and tug availability. A simple harbor scenario involving straight legs (¾ nm in length and 800 feet wide) and a widened 45° turn was used. The water/depth ratio was 1:15. The ships experienced a northwesterly wind fluctuating around 30 knots and a flood current of 1 knot in the channel direction. During the experiment each pilot performed three successive runs on his ship, followed by a final run that involved a complete engine and rudder failure just at the entrance to the turn. The data from the experiment were the examined qualitatively and selected performance measures were subjected to statistical analyses. On this basis, observations and conclusions were made relating to the comparisons indicated previously.

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Prepared By

William McIlroy, Ph.D.
CAORF Research Staff

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EXECUTIVE SUMMARY

TUG USAGE FOR CONTROL AND DECELERATION IN RESTRICTED WATERWAYS

BACKGROUND

In restricted harbor areas a ship encounters many environmental and physical factors that greatly affect its maneuverability and its safety: shallow water, bank effects, winds, currents, traffic, moored ships and fixed structures. As a result, the U.S. Coast Guard and Intergovernmental Maritime Consultative Organization (IMCO) have given top priority to studies of the inherent maneuverability of existing and future ships under normal maneuvering conditions and when maneuverability is impaired due to engine and/or rudder failures.

Limitations in shiphandling capability can impose significant safety and economic penalties through the need for reduced speeds and use of tug support. Ship size may limit use of an existing harbor. Substantial modifications may be required, therefore, to provide larger channels in which the ship can travel safely.

The environmental conditions for safe operations may be limited by the degree of ship maneuverability, so that a given vessel class may not be permitted to enter the harbor except with the assistance of tugs.

Techniques that could be used to improve the maneuvering characteristics of these large tankers have been studied by the U.S. Coast Guard. They could involve expensive modifications and/or use of methods that are beyond the present state-of-the-art. The most promising techniques for existing ships appear to be, simply, the use of slower approach speeds and more efficient use of available tug power.

The towage power required is still based on somewhat arbitrary guidelines, and it is imperative, from both an economic and safety viewpoint, that more definitive methods of assessment be developed as soon as possible. If it were possible to minimize the number of tugs consistent with safety, the pilot's workload in positioning and transferring tugs would also be considerably reduced. There would be less confusion in receiving and interpreting orders between the pilot and the tugs, and between the tugs themselves. The operation could also turn out to be less costly, although highly maneuverable and higher powered tugs may be required. When conventional tugs are used in a multi-tug operation, there are times, particularly during berthing, when only a number of them are actually contributing. With the newer types of highly maneuverable tugs, berthing can be performed much more efficiently and safely.

The Maritime Administration, in conjunction with the U.S. Coast Guard, has planned full-scale, instrumental trials to compare the effectiveness of alternative types of tugs and techniques for docking.

The overall intent of these sea trials was to obtain data that could be used in the ship-tug dynamics simulation at the Computer Aided Operations Research Facility (CAORF), so that realistic simulations of low speed maneuvers using tugs can be ensured.

The information derived from the first of these series of tests, carried out in the Chesapeake Bay area in 1978, was incorporated in the design of the present experiment. This test involved a highly maneuverable 1,000 BHP Wilmington Launch Tug, the "Tina", maneuvering a 25,000 DWT tanker, the "Yukon", at speeds between zero and six knots.

To provide some answers to these questions, a series of on-line experiments on tug usage were planned for CAORF. These are designed to obtain information on present techniques, to analyze the resulting performance using these techniques, to search for methods of improvement, and to develop optimal strategies, which can be incorporated in future training routines.

These experiments will be performed to determine the variability in pilot operating procedures for manipulating tugs in a restricted waterway when subjected to external environmental forces. They will encompass the deceleration, stopping, turning, and finally berthing (and unberthing) phases of the operation, in addition to their use in assisting ships with imparied maneuverability.

The objectives of this series of experiments will be to establish requirements for the minimum number of tugs, their types, horsepower and method of attachment, in relation to ship characteristics and environmental factors.

The present experiment is concerned principally with the use of tugs during the deceleration and stopping phase, under normal conditions and also in the case where a complete failure of engine and rudder (amidships) occurs without recovery.

EXPERIMENT DESCRIPTION

This present study represents the first of a three-part investigation into tug usage in harbors. There are three essential phases in these tug operations:

1) Use of tugs for deceleration and control.
2) Tugs in emergency procedures.
3) Use of tugs for turning and berthing.

Tugs are required for this third operation and for safety reasons should be available at all times in restricted waterways in case of an engine/rudder failure which could inevitably end up in a collision, ramming or grounding. If tugs are not already in the attendance mode (that is, tied up to the ship), but merely escorting the ship (accompanying it at some distance but not attached), the time lapse following an emergency before the tugs can become effective may be excessive so that a grounding cannot be avoided. In narrow waterways the technique would appear to be to limit the ship speed and provide tugs in the assistance mode at all times.

The present experiment has two basic objectives:

- o To investigate the effectiveness of two tugs of 2,000 HP each or four tugs of equivalent total horsepower in assisting two size tankers, a conventional 80,000 DWT and a less familiar 250,000 DWT, in negotiating a hypothetical harbor under realistic environment conditions.
- o To investigate the effectiveness of two tugs of 4,000 HP each or four tugs of 2,000 HP each in

assisting the 250,000 DWT tanker in the same harbor and environment.

The study falls essentially into two phases: Phase 1, where the ship is maneuvered with tugs in attendance, but inactive unless an emergency situation (due to equipment failure only) arises; and Phase 2, where the ship can use the tugs in attendance at all times to initially reduce speed and effect the turning and final stopping maneuvers. In Phase 1 the tugs are tied up alongside the ship for almost immediate action should a mechanical equipment failure occur. However, they are not to be used where the dangerous situation arises due to mishandling of the ship. This situation has been referred to as "inactive" in this report. On the other hand, in Phase 2, the tugs are also tied up to the ship, but may be used at any time during the transit ("active") for assisting in the control of the ship.

The requirement is made in both cases to be stopped relative to the ground at a point about 3/4 n miles outside a 45° turn, in the presence of a strong wind and a flood current.

The subjects participating in Phase 1 were all experienced harbor pilots, while those in Phase 2 were experienced docking pilots.

The 48 pilots were drawn from essentially three different areas of the East Coast of the United States (New York, Boston, and Delaware). One pilot from St. Lawrence Seaway and two from Houston were also involved.

EXPERIMENT DESIGN

The experiment design is shown in Table ES-1. Each phase is subdivided into divisions A and B: Phase A is further subdivided into Groups 1 and 2. In Phase A, the tug power available is 4000 BHP and can be distributed among either two or four tugs. Group 1 and Group 2 subjects, comprising four pilots each, are conning an 80,000 DWT tanker and a 250,000 DWT tanker, respectively. In Phase B, the available tug power is doubled, and Group 3 test subjects are assigned to the larger ship only. The tugs were considered to be essentially scaled versions of the basic 1000 BHP 'Tina' tug.

The three groups were given a familiarization run without wind and current; this was designed to acquaint them with the ship characteristics, the scenario, navaids, etc.

Each subject in Phases 1A and 1B also made three replicate runs with tugs in attendance but always inactive, and finally experienced a complete failure at a designated point (in line with buoy 8), at which point the tugs could be activated. The complete failure represented a loss of engine power with the helm fixed amidships. This type of failure compels the pilot to make full use of his tug support.

In Phases 2A and 2B, the experimental procedure was very similar - ship, wind and current conditions, and tug configurations. The three groups of eight subjects apiece ran the initial familiarization run, and the three replicate runs with tugs actively in attendance. In this way, the tugs could be used at anytime as desired to augment the rudder and rpm in control. These subjects also experienced a complete failure (in line with buoy 8) on their final run and modified their strategies to use tugs completely for control during the remainder of the passage.

TABLE ES-1. EXPERIMENT DESIGN

Phase 1 - Tugs in Attendance But Inactive					
1A - 4,000 HP				**1B - 8,000 HP**	
Group 1 - 80K		**Group 2 - 250K**		**Group 3 - 250K**	
2 Tugs	**4 Tugs**	**2 Tugs**	**4 Tugs**	**2 Tugs**	**4 Tugs**
4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects
Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn	
Phase 2 - Tugs Active					
2A - 4,000 HP				**2B - 8,000 HP**	
Group 1 - 80K		**Group 2 - 250K**		**Group 3 - 250K**	
2 Tugs	**4 Tugs**	**2 Tugs**	**4 Tugs**	**2 Tugs**	**4 Tugs**
4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects
Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn	

1 Familiarization Run for Ship, Scenario - No Wind or Current
3 Replicate Runs
1 Complete Failure

HARBOR DESCRIPTION

The simple channel configuration used in this experiment is shown in Figure ES-1. The spacings between buoys along the straight legs are uniformly 3/8 n mile. The channel is 800 feet wide along the straight legs and is widened in the turn to approximately twice this value.

The speed of the ships on entering the harbor from the sea outside (midway between buoys 3 and 4, Figure ES-1, where tugs can begin to hook up was seven knots through the water in all cases. The scenario presents an initial deceleration zone of 3/4 n mile. During this time, the ship can be slowed down progressively, if necessary, to permit the tugs to pass towing hawsers and safely lash up alongside the ship. In order to simulate real-world conditions a five-minute time delay was imposed after entering the channel before the tugs could become effective. This is then

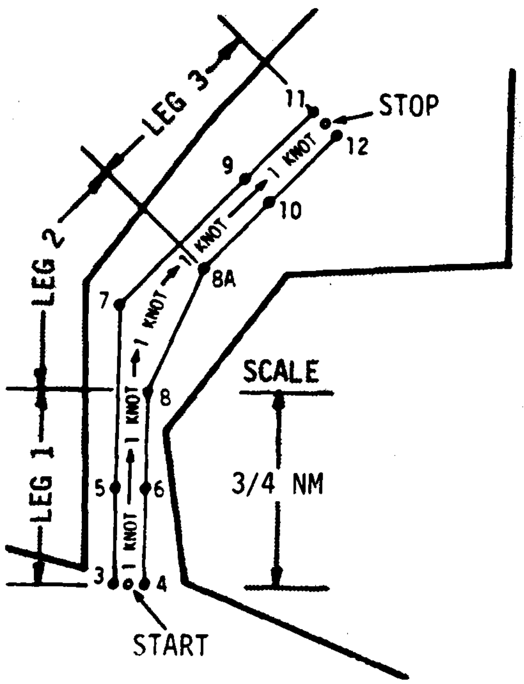


Figure ES-1. Harbor Configuration

followed by a 45° turn (which represents both the recommended maximum heading change acceptable in a harbor waterway, and also a smooth transition curve radius of at least five times the length of the biggest ship using the channel). On emerging from the turn, the ship can eventually slow down to stop midway between the gated buoys 11 and 12, three quarters of a nautical mile (or approximately four or five ship lengths) along this third leg.

CHANNEL DIMENSIONS

The water depths inside the channel and outside have been chosen so that the depth/draft ratio of 1.15 is the same for both the fully loaded 80,000 DWT and the 250,000 DWT tankers used in this experiment. It was decided to select a constant depth/draft ratio for the two ships so that shallow water effects would be the same for each. Further, the relative dimensions of the submerged channel were selected so that the bank effect experienced by both ships would be about 38% of the bank effect they would individually experience in the presence of a fully emergent bank. Consequently, both the shallow water and bank effects were comparable for both ships used in this experimental program.

ENVIRONMENTAL CONDITIONS

Wind. The wind in the harbor was assumed to be gusting with a strength of 30 ± 10 knots from the NW approximately ($315^{\circ} \pm 30^{\circ}$).

Current. A flood current was assumed to flow in the channel direction at 1 knot speed. In the 45° turn it flows along the transition arc of radius 5,100 feet, which is tangential to the centerline of leg 1 and leg 2 at the buoy locations 8 and 8A, respectively.

TUG SIMULATION

For the present experiments the "simple" tug simulation procedure was used since the advanced tug simulator was not available until later. Fortunately the assumptions implied in using this simplified form (constant thrust and angle of application independent of ship speed, tug capabilities, etc.) could be used with some confidence based upon the results of the sea-trials involving the "Tina" (a 1,000 HP tug with 360° steerable propulsion units and Kort nozzles) and the 25,000 DWT USNS "Yukon." These tests were performed to measure static and dynamic bollard pulls at angles to the ship's centerline while the ship and tug were proceeding at speeds from zero to six knots. In addition, the tug's effectiveness when trailing and pulling with astern thrust was assessed. An examination of the data indicated that if a maximum bollard pull of a constant 27,000 pounds were adopted independent of ship speed (but less than 6 knots), hawser angle and propulsion unit angle, the maximum error would never exceed 10%. Such an assumption was ideal for our purposes, and consequently tugs with "Tina's" characteristics were built into the present experiment. In addition, this same tug with its hydrodynamics and aerodynamics etc. was to be used initially in the advanced tug simulator. During the initial verification and validation phases of this advanced tug model the appropriateness of the simple model used here would become apparent. The characteristics of the "Tina" tug are tabulated below in Table ES-2.

TABLE ES-2. CHARACTERISTICS - WILMINGTON LAUNCH TUG "TINA"

Length Overall	65.0 ft.
Beam, Molded	26.0 ft.
Draft, Molded	9.0 ft.
Draft to Bottom of Skeg	10.5 ft.
Displacement (Design)	127.5 tons
Brake Horsepower	1,000 HP

Propulsion. Two diesel engines coupled to Murray and Tregurtha 360-degree steerable propulsion units with propellers in Kort nozzles. The two propellers are mounted aft. The tugboat is designed to operate as a tractor tugboat when going astern.

Propellers. Right-hand, four-bladed, Kaplan type; 5.33 feet diameter in a Kort nozzle.

These tugs can contribute maximum thrusts of the order of 27,000 pounds on a continuous basis at any heading and, hence, without the tug having to be repositioned control of Ownship can be maintained at all times. Full thrust can be obtained aft and broadside as well as forward, which permits a minimum amount of line handling while docking.

The magnitude of horsepower to be assigned to the tugs in this experiment was determined after closely examining literature dealing specifically with actual tug operations throughout the world.

There appeared to be an extremely wide variation in specifications for the required total tug horsepower as related to ship size. Based on the available information, a total bollard pull of 50 tons was considered appropriate for the maneuvers in this experiment. This value could be achieved by using either four 1,000 HP or two 2,000 HP tugs of the "Tina" type. As a consequence, these tug types were incorporated in the present design. Where 2,000 and 4000 HP tugs were used (Phases 1B and 2B) these were considered to be simply scaled versions of the basic tug.

When two tugs were used in the present experiment, they could either be attached at the bow and the stern on soft lines, or be free to push against the ship hull at attachment points initially assigned by the pilot on first entering the channel. When four tugs were employed, they were free to operate on lines or in the pushing mode at points assigned by the pilot.

Tug Display

During the simulation exercise, the pilot was at a disadvantage in that he could not check tug locations by peering out of the wheelhouse. To compensate for this deficiency, the pilot was presented with a display of the ship's planform and the relative tug positions using a closed-circuit TV monitor.

OWNSHIP AND TUG CHARACTERISTICS

Two tankers were used as Ownship in these experiments (Table ES-3). They represent a large ship of tonnage familiar to most pilots in US ports (80,000 DWT), and one of a very large tonnage that is familiar to only a few pilots (250,000 DWT).

For both these ships the following simulations were available and were used during these experiments:

1) Zero/low speed hydrodynamics.
2) Aerodynamics.
3) Shallow water effects.
4) Bank effects.

However, squat and modified trim in restricted shallow waters and wave forces (all of which would be small in this scenario) were not included in the simulation.

EXPERIMENT PROCEDURE

Preliminary Operations

Before performing his experimental runs, the pilot was briefly introduced to the CAORF bridge and its equipment, the properties of the visual scene and the specific procedures that would be used. The pilot was then briefed by a member of the CAORF staff who discussed the scenarios, channel dimensions, banks, shallow

TABLE ES-3. OWNSHIP CHARACTERISTICS		
	250 DWT	**80K DWT**
Length (L)	1,085 ft.	763 ft.
Draft (T)	65 ft.	40 ft.
Beam	170 ft.	125 ft.
Depth/Draft	1.15	1.15
Ahead HP	36,000	24,000
Prop. Dia.	29.2 ft.	25 ft.
Max. Rudder Angle	35°	35°
Rudder Area (A_R)	1,302 ft.^{2}	517.5 ft.^{2}
Ar/LT $\frac{\text{Rudder Area}}{\text{Underwater Area}}$	0.018	0.017

water, winds and currents, ship and tug characteristics, operating procedures and requirements. He was then provided with a chart of the harbor and a detailed printed booklet duplicating the details of the verbal briefing. The pilot could therefore refer to this document and chart at any time during the experiment should he have any questions. He was told he would perform five runs in all, the first for familiarization and subsequent runs for improvement of techniques. He was not told at any time to expect a complete mechanical failure.

At the end of each run a short formal briefing was held with each subject by a member of the CAORF Research staff. Questions regarding the subjective reactions to the run, vessel handling, wind and bank effects, tug handling qualities, etc., were explored. At the end of the series of five runs a final debriefing session was held to obtain an overall assessment of the experiment from the pilot and indications of where in his judgement certain aspects may have lacked realism.

Data Collection

A variety of sources were used for data collection during the running and analyses of the experiment. The major performance measures were obtained or derived from computer summary datalogs, ship's bridge data sheets, and debriefings. The primary source for all objective data during the actual experiment runs was the "playback tape." This is a magnetic recording of each run, taken at a fixed time interval, of important computer and ship state parameters (numbering well over 1,000 items). The recording

rate for the experiment was once every 10 seconds.

Computer Summary Datalogs

Computer summary datalogs are printouts from the playback tapes. This information was made available as hard copy printouts at the end of groups of runs. A total of 46 items were obtained on the printouts and used in the subsequent analyses.

Data Presentations

Data collected during the experiment are presented in the following format for visual interpretation and qualitative evaluation that will complement the conclusions of the statistical analyses of the same data.

- o Ship track plots, derived from the ship's dimensions, the coordinates of its center of gravity (X_0, Y_0) and its heading as recorded in the data summary at two minute intervals.

- o Simultaneous plots of rudder angle, rudder moment and engine speed variation with time over the duration of runs, for both the active and inactive tug modes. These data are obtained directly from the data summary. For the active mode these quantities are shown along with the corresponding plots of tug forces and tug moment.

- o Plots indicating the mean distance off the assigned track (the centerline in legs 1 and 3, and the transition arc in leg 2) at 400-foot intervals. The individual values of distance off-track were calculated from the ship coordinates at the interpolated time corresponding to each 400-foot increment using the information in the data summary. The data corresponding to the subjects in each combination of factors considered, for example, ship size, tug mode and tug number, were then averaged to obtain the mean distance off-track at that location. At the same time the standard deviation and the extremes of these individual measurements were estimated. The mean, standard deviation and the extremes are all depicted on the plots.

PERFORMANCE MEASURES

The feasibility of conventional performance measures was examined for use in narrow waterways, and as a consequence, new concepts for a combined performance measure and an "inherent risk" factor were introduced. These measures could more realistically account for the ship's state, the control variables *and* the waterway geometry, simultaneously.

Performance has conventionally been measured in terms of the RMS deviations off an assigned track and the RMS rudder angle that was used. The RMS deviation off-track of the ship's center of gravity, however, must be considered in conjunction with the swept path to indicate the closeness of the ship's extremities to the channel boundaries. In itself it does not give a measure of the nearness to grounding. The RMS rudder angle indicates the amount of rudder that was used to perform the transit and, consequently, the amount of rudder that remains to control the ship should an emergency situation arise. Again this measure in itself is not sufficient. The amount of rudder moment that can be exerted by

the ship is dependent not only on the amount of rudder but also the rudder efficiency; the rudder efficiency is a function of hull speed *and* engine speed, and importantly the direction of propeller rotation. This is demonstrated very clearly in the time histories of rudder moment, rudder angle and engine RPM. In these figures it can be seen that in the final deceleration stage, the engine is going full astern and the rudder angle is saturated. However, due to the ship's low speed the actual rudder moment is very small compared to its values at prior times. That is, as the ship decelerates, it effectively loses all its rudder control efficiency. It would therefore be more realistic to adopt a performance measure of RMS rudder moment or RMS "effective" rudder angle to account for not only actual rudder angle but also the ship's hull speed and engine speed during the transit.

As a consequence of these considerations a new concept of a combined performance measure was adopted. This new measure or performance index, denoted by J, contains:

a) effect of rudder and deviation off-track
b) "inherent" risk
c) tug moment.

(a) The contribution of rudder is the mean value of the sum of the squared rudder angles normalized with respect to the maximum rudder angle, 35°.

The contribution of deviation off-track is the sum of the squared deviations normalized with respect to a bias value of 100 feet. It was considered that pilots would be quite satisfied with their performance if their ship lay within 100 feet either to the left or right of the designated track, and would not necessarily make any effort to return the ship exactly to the track. Especially in the presence of wind they may prefer to lie to windward. The subsequent experiment tended to justify this value.

These two contributions do not tell the complete story, for they indicate that a low value of the performance index, indicating good performance, can be achieved by travelling at higher speeds. Higher ship speeds increase the rudder efficiency, decrease the rudder angle requirement, minimize the wind influence and produce better trackkeeping. However, this does not consider the possibility of mechanical (rudder and engine) failures taking place at any time. In this case, it would be preferable to be travelling at low speed, contrary to the above conclusion!

To include the possibility of a failure at any point along its track and the "inherent" risk of grounding, the following concept was developed.

(b) The vulnerability of the ship at any instant is a function of the state and the actual position of the ship -- its location, heading, turn rate, speed, its dimensions *and* the contours of the boundaries of the waterway. In the event of a rudder and/or engine failure, the time ("recovery time") before the failure can be corrected, or before the tugs can restore the ship to follow a safe track and prevent grounding, is an extremely important factor. In the subsequent analysis three values for recovery time were assumed -- 2-1/2, 5 and 10 minutes, respectively. Assuming that the ship's speed and direction remain unchanged following the failure its trajectory can be calculated and the shortest time for the first impact on the surrounding boundaries estimated. In this way the "inherent risk" of grounding can be

established. If the time for the ship to strike the nearest boundary is less than the recovery time then a grounding will take place and a value of unity will be assigned for this time. Conversely, if the impact time is greater than the recovery time, a zero value is assigned to the risk. In this way corresponding to each point along the ship's trajectory a value can be assigned, either 0 or 1, which is then accumulated in time. The ratio of the number of grounding possibilities and the total time in the channel section (α) represent the percentage of time the ship is in danger of grounding should a failure occur. This is an important addition to the performance index as it is speed-dependent. Even when the ship is perfectly on track, there is always an inherent risk if the speed exceeds a certain limit when negotiating turns in restricted waterways.

This was demonstrated by a simple calculation for the ship following the centerlines and the transition arc. For no inherent risk to be possible the calculation indicates that the ship speed should be about three knots or less in the turn. On the other hand, a speed of four knots or more could lead to an inherent risk of unity! This shows that the small margin of one knot could be critical should a complete failure take place.

When tugs are also being used for controlling the ship, the state and the position of the ship is dependent on the prior tug usage. However, any assistance from the tugs following a failure is not accounted for in the calculation of the inherent risk factor. Some time will elapse before they can effectively divert the ship's path, and their effect on inherent risk will be principally in reducing the recovery time. Sample off-line calculations demonstrated the relatively slight influence of instantaneous tug assistance on the advance and transfer of the ship following failure.

(c) When tugs are being actively used for controlling the ship, an additional tug contribution is added to the performance index, namely, $(^{RMS}N_{TUG}/N_{MAX\ TUG})^2$. This is similar to the rudder contribution, and represents the degree to which tugs are being used in controlling the ship relative to their full potential. Similarly it also provides a measure of the amount of tug moment remaining that is available when needed.

Only tug moment was included in the performance index since we are mainly concerned with control. No consideration has been given to the lateral and longitudinal forces that produce these moments, but which in themselves play an important role in maintaining the ship on a safe track, particularly during the final deceleration stages of leg 3.

The final representation of the performance index J used in the subsequent analysis is

$$J_L = \alpha_i + \left(\frac{Y_{rms}}{100}\right)^2 + \left(\frac{\delta_{RMS}}{35}\right)^2 + \left(\frac{N_{TUG\ RMS}}{N_{MAX}}\right)^2$$

where index i (=1, 2, 3) refers to the assumed recovery times (2-1/2, 5, 10 minutes) respectively.

DATA ANALYSIS

The data collected during the investigation were examined in two ways: qualitatively by visual examination of simulataneous plots of ship tracks and corresponding controls, and quantitatively by statistical methods.

Qualitative Analyses

The qualitative evaluation was made by examining, comparing, and correlating the various forms of graphical data derived from the experiment. These were studied separately for the non-failure and the failure conditions.

- o **Observations on Non-Failure Runs.** The following categories were examined in detail and the observations illustrated by using selected examples from the many experiment runs available: (a) ship ground tracks, (b) rudder angle, engine rpm and rudder moment, (c) tug forces and moments, and (d) mean track line.

  Conclusions are presented in the final section of this Executive Summary.

- o **Observations on Failure Runs.** It was qualitatively established that the success of maneuvers using tugs following a complete engine and rudder failure depends upon:

  - The initial conditions of the ship at the time of failure (heading, rate or turn, distance off-track, etc.).
  - The speed of the ship at that time.
  - The time lag before tugs are used by the pilot.
  - The tug horsepower available relative to the size of ship.
  - The method of tug deployment to obtain maximum effect, as related to the dynamics of the ship (its linear and angular momentum).
  - The intensity of wind and current effects and a knowledge of their influence on ship motion.

The simultaneous analysis of the ship track and tug forces clearly demonstrated the importance of these factors, information that can be carried into real life operations.

Statistical Analyses

The statistical analyses were based on Analysis of Variance procedures (Anova 1 and Anova 2) on the experimental data involving the two main comparisons:

1) Ship type (80,000 DWT and 250,000 DWT tankers)

2) Available Tug horsepower (4000 and 8000 BHP).

Two Anova Source Tables were generated that show the significant dependencies of the 23 performance measures on the various factors (main effects) and their interactions to significance levels of 0.001, 0.01, and 0.05.

In order to understand quantitatively the importance of the various factors more fully it was necessary to examine in detail the higher order significant interactions. This was done and the final results are described for a selected number of the performance measures considered - mean speed, swept path, distance-off-track contribution, rudder contribution, tug moment contribution, inherent risk factor, and the combined performance measure.

CONCLUSIONS

As a result of the qualitative and quantitative analyses of this experiment, the following significant conclusions have been drawn:

- The track plots did not show any significant difference in the outcome of the shiphandling techniques employed by the harbor pilots and by the docking masters. Both groups demonstrated a wide variation in shiphandling techniques using conventional rudder and engine controls to maneuver in the first leg and the turn.

- Even though the docking masters had tug support readily available, they did not find it necessary to use it, even with the larger ship, until entering the final deceleration stage.

- This final deceleration stage, in the presence of the flood current and beam wind, proved to be most critical. Tug assistance was necessary, especially with the larger ship.

- Even when the pilots of the 250,000 DWT tanker had 8000 HP available, under normal conditions and in the final deceleration phase, they still used about the same amount of RMS tug moment on the ship as they did when only 4000 HP was available. In their opinion, this amount was apparently sufficient for controlling the ship.

- At the 4000 HP level, there was a significant increase in tug moment (in the final stages) when four tugs rather than two were used. At the higher level, much more tug moment was produced when using only two tugs.

- The mean speed of the 250,000 DWT tanker was always higher than that of the 80,000 DWT ship in the first leg and in the turn but comparable in the third leg. This higher speed greatly reduced the influence of wind and current. With replicate runs, the speed of the larger ship did not change. The 80,000 DWT tanker, however, started slowly, experienced problems with wind and current, and in its next run increased speed. The speed did not change significantly in the third run. Due to its higher speed in the turn and also its higher inertia, the larger ship required considerable tug assistance in safely decelerating in the third leg.

- The tug usage with the 80,000 DWT tanker was negligible throughout the transits, indicating that pilots were capable of handling this size ship without tugs under normal non-failure conditions.

- Due to its higher speed, the inherent risk of grounding was always greater with the larger ship. As the 80K ship increased speed in its first two runs, it improved its deviation off track in the turn, reduced the amount of rudder angle it was using, but increased the danger of grounding should a failure occur.

- The results of a simple inherent risk analysis indicated that even under ideal conditions in this channel geometry a speed of three knots should not be exceeded in the turn. This would minimize the possibility of

grounding in the event of a complete mechanical failure (assuming a five minute recovery time). At four knots, on the other hand, the risk would be close to 100 percent. This indicates that even small time lags and small speed differentials are critical to a successful passage. These calculations are well substantiated by the large number of groundings that actually did occur in the experiment following a failure at the beginning of the turn (leg 2).

- The inherent risk factor was highest in the turn, and smallest in the final leg. This is due to the ship speed and principally the limitations in dimensions of the waterway in the channel elbow.

- The experiment showed that when a complete mechanical failure occurred with the 250,000 DWT tanker, there were 13 groundings out of a total of 16 runs. Therefore, it would appear that 4000 HP was insufficient to prevent grounding of these large ships at the speeds they were using. With 8000 HP tug power available, there was a considerable improvement, but 8 groundings out of 16 runs still took place. The important factor appears to be the ship response time at these speeds.

- The occurrence of a complete failure presented great difficulty to the majority of the pilots in this scenario, particularly with the larger ship at the lower horsepower. Even those pilots who avoided grounding experienced considerable difficulty at various sections of the harbor during transit.

- There were large variations in the time lapse after failure before the pilots applied their tug power. This time lag is critical to minimizing the possibility of grounding. It corresponds to distance travelled by the ship in the limited maneuvering area of the first leg and the turn.

- Groundings with the 80,000 DWT tanker occurred principally in the final leg where the ship was very susceptible to wind and current. Tugs were able to help the ship complete the turn, but the occurrence of grounding appeared to be critically dependent on its closeness to the centerline and the angle of crossing the centerline as it enters the final leg.

- The 250,000 DWT tanker generally grounded in the turn. Because of its greater speed and its considerable inertia, it did not respond sufficiently to the tug forces at either power level and, consequently, in most cases failed to make the turn.

- The occurrence of grounding is clearly related to the condition of the ship at the time of failure (whether it has already initiated its turn, its speed, the tug power available, etc.) and, importantly, the pilot's time lag in applying his tugs, their subsequent use, and the ship response to these forces.

- There were indications of a dependence of mean speed of the 250,000 DWT tanker on tug mode and tug number, at the 8000 HP level, but not at the 4000 HP level.

- The swept path increased from leg 1 to leg 3, and in the final phase, there appeared to be a tug number and tug mode dependence.

- The deviation off-track did not change significantly between the two ships nor with tug mode. However, it apparently depended on whether two tugs or four tugs were being used. The largest values occurred in the turn. In the case of the smaller ship in its initial run a larger deviation occurred in the turn when the four tug configuration was used. For the 250,000 DWT tanker, however, the deviation was independent of tug number. It should be remembered that tugs were rarely used with both ships except in the final leg where the deviation off track tended to be reasonably constant.

- A greater amount of rudder was used by the larger ship despite its higher speed and, consequently, greater rudder effectiveness. This is indicative of the severity of the environmental effects due to ship size. The amount of rudder used increased from leg 1 to leg 3. In the final leg, although a large amount of rudder was being used, the rudder is very ineffective. During the time the engine is running in reverse to produce a rapid deceleration, it loses the turning capability of the rudder almost completely. With consecutive runs, the amount of rudder did not change on the 250,000 DWT ship. However, on the 80,000 DWT tanker, particularly in leg 2, the amount of rudder decreased with the second replicate run, due to the increase in speed in this ship with repetition.

  In the third leg, comparably large amounts of RMS rudder were used by both ships.

- A simultaneous rudder and engine failure without recovery has a very low probability of occurrence; yet, should it occur, the consequences could be serious in relatively confined waterways. The probability of the occurrence of an engine failure alone or a rudder failure alone, with or without recovery in a finite time is much greater.

  A further experiment will investigate the tug requirements and pilot behavior in these cases also.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In restricted harbor areas a ship encounters many environmental and physical factors that greatly affect its maneuverability and its safety: shallow water, bank effects, winds, currents, traffic, moored ships and fixed structures. As a result, the U.S. Coast Guard and IMCO have given top priority to studies of the inherent maneuverability of existing and future ships under normal maneuvering conditions and when maneuverability is impaired due to engine and/or rudder failures. Limitations in shiphandling capability can impose significant safety and economic penalties through the need for reduced speeds and use of tug support. Ship size may limit use of an existing harbor. Substantial modifications may be required, therefore, to provide larger channels in which the ship can travel safely. The environmental conditions for safe operations may be limited by the degree of ship maneuverability, so that a given vessel class may not be permitted to enter the harbor except with the assistance of tugs. Although Card et al. (1979) surveyed several techniques that could be used to improve the maneuvering characteristics of these large tankers, the most promising techniques for existing ships appear to be, simply, the use of slower approach speeds and more efficient use of available tug power. As tanker size has progressively increased, the role of the tug has therefore become more crucial to safety of passage. Strategies in using braking tugs and rudder tugs in sea trials have shown them to be very effective for improving stopping and maneuvering capabilities. In addition, at these slower speeds, the shiphandler can take advantage of the "kick effect" to obtain positive control, when required. The tugs can also be attached more easily and safely, the tug effectiveness is increased considerably, so full advantage can be taken of the available tug power.

There is a wide variation among techniques and practices for using tugs in different harbors throughout the world. The location of the port and the prevailing weather conditions create specific problems which, in turn, dictate the berthing procedures that should be adopted, and the minimum number of tugs required for ships of given sizes. The towage power required is still based on somewhat arbitrary guidelines, and it is imperative, from both an economic and safety viewpoint, that more definitive methods of assessment be developed as soon as possible. Some ports assign tugs according to ship tonnage; whereas in others the number to be used particularly in view of the rapidly escalating costs of new tug vessels and charges for tug services, is left to the discretion of the pilot. If it were possible to minimize the number of tugs consistent with safety, the pilot's workload in positioning and transferring tugs would also be considerably reduced. There would be less confusion in receiving and interpreting orders between the pilot and the tugs, and between the tugs themselves. The operation could also turn out to be less costly, although highly maneuverable and higher powered tugs may be required. When conventional tugs are used in a multi-tug operation there are

times, particularly during berthing, when only a number of them are actually contributing. With the newer types of highly maneuverable tugs, berthing can be performed much more efficiently and safely. Some pilots prefer to use a small number of powerful tugs, whereas others prefer to split up the available power by using more smaller tugs. In the US and Japan, the tendency is for tugs to be used alongside, whereas in Europe they are attached by soft lines. The specific system is dictated principally by the maneuvering space that is available, e.g. in the U.S. the ports are in enclosed waterways, whereas in Europe they are more often exposed directly to the sea.

Recently, low speed maneuvering techniques involving tugs have been receiving much more attention. Now, a number of documents are available which describe the actual procedures used in various ports, for instance: (1) The Japan Workvessel Association (1977) presented a very comprehensive survey of operations with research results, concerning braking tugboats of various degrees of maneuverability; (2) the National Maritime Institute (NMI) (1978) studied actual berthing procedures at the port of Southampton in the UK using tracking stations, onboard observations, and aerial photography to obtain the positions and attitudes of tugs relative to the ship; (3) the National Ports Council (1977) reviewed tug procedures in the UK and in Europe, and presented practical conclusions and recommendations for improvement; (4) The First International Symposium on Ship Approach and Berthing Maneuvers (1977) presented extremely valuable information from the viewpoint of both the seaman and the engineer; and (5) Atkinson (1980) discussed various tug types and their use throughout the world, and offered suggestions on a selection of tug types and possible features of the optimal tug. In addition two basic shiphandling texts have been made available recently that describe many of the practical aspects of tug handling (Willerton (1980), Armstrong (1980)).

MarAd, in conjunction with the U.S. Coast Guard, has planned full-scale, instrumented trials to compare the effectiveness of alternative types of tugs and techniques for docking. The first series of tests was carried out in the Chesapeake Bay area in 1978, Kelley et al., (1979), and involved a highly maneuverable (steerable propulsion with Kort nozzles) 1,000 BHP Wilmington Launch Tug, the Tina, maneuvering a 25,000 DWT tanker, the Yukon, at speeds between zero and six knots. The information derived from these tests was incorporated in the design of the present experiment. In contrast to the above, a second series of trials was carried out at the same time at Valdez, Alaska involving a 120,000 DWT tanker and a conventional twin screw tug of 5,750 BHP, (Lancaster, 1978). A further series of sea trials were carried out in the Strait of Juan de Fuca, Washington in January, 1981 (Altmann, 1981) and in Hampton Roads, Va., in October 1981.

The overall intent of these sea trials was to obtain data that could be used in the ship-tug dynamics simulation at the Computer Aided Operations Research Facility (CAORF), so that realistic simulations of low speed maneuvers using tugs can be ensured.

As the full ship-tug dynamic simulation was not ready for this present experiment, a simplified tug treatment was necessary. Fortunately, the characteristics of the Tina tug demonstrated in these sea-trials are such that the the basic simplifying assumptions that are made are not unrealistic.

1.2 OBJECTIVES

A series of on-line experiments on tug usage have been planned for CAORF, of which the present experiment was the first. These will be designed to obtain information on present techniques, to analyze the resulting performance using these techniques, to search for methods of improvement, and to develop optimal strategies, which can be incorporated in future training routines.

These experiments will be performed to determine tne variability in pilot operating procedures for manipulating tugs in a restricted waterway when subjected to external environmental forces. These investigations will encompass the deceleration, stopping, turning and finally berthing (and unberthing) phases of the operation, in addition to their use in assisting ships with impaired maneuverability.

The objectives of this series of experiments will be to establish requirements for the minimum number of tugs, their types, horsepower and method of attachment, in relation to ship characteristics and environmental factors. The present experiment is concerned principally with the use of tugs during the deceleration and stopping phase.

CHAPTER 2

EXPERIMENT METHODOLOGY

2.1 EXPERIMENT DESCRIPTION

This present study represents the first of a three part investigation into tug usage in harbors. There are three essential phases in these tug operations:

1) Use of tugs for deceleration and control.
2) Tugs in emergency procedures.
3) Use of tugs for turning and berthing.

Tugs are required for this third operation and for safety reasons it would be beneficial to have them available at all times in restricted waterways in case of an engine/rudder failure which could inevitably end up in a collision, ramming or a grounding. In this report, the following terminology is used which may be unfamiliar to many readers. Tugs are said to be in the "attendance mode" when they are already attached to the ship at positions selected by the pilot. They are therefore available to exert control on the ship at short notice, provided their locations do not have to be changed. Tugs are "active" in the attendance mode when they can be called upon to exert control at any time. They are "inactive" in the attendance mode, when they are not permitted to be used unless there is a drastic (combined engine/rudder) failure of the equipment. In the experiment to be described a group of harbor pilots was provided with tugs in the attendance mode but inactive; the group of docking masters was assigned tugs in attendance but these were active, i.e., they could be used at any time. The term "assistance mode" is used to refer to tugs in escort, which are unattached to the ship, and will required a finite period of time to make up their lines when needed. If tugs are not already in the "attendance mode," but merely escorting the ship, the time lapse occurring after an emergency takes place and before they can become effective may be excessive so that a grounding cannot be avoided. Finite times are also required to remedy a rudder failure (at least three minutes) or an engine power failure (at least six minutes), so that again these efforts will be unable to save the ship. In narrow waterways the technique would appear to be to limit the ship speed and provide tugs at least in the "assistance mode" at all times. The present experiment has two basic objectives, (a) to investigate the effectiveness of two tugs of 2,000 HP each or four tugs of equivalent total horsepower in assisting two size tankers, a conventional 80,000 DWT and a less familiar 250,000 DWT, in negotiating a hypothetical harbor under realistic environmental conditions and (b) to investigate the effectiveness of two tugs of 4,000 HP each or four tugs of 2,000 HP each in assisting the 250,000 DWT tanker in the same harbor and environment. The study falls essentially into two phases: Phase 1, where the ship is maneuvered with tugs in attendance, but inactive unless an emergency situation (due to equipment failure only) arises; and Phase 2, where the ship can use the tugs in attendance at all times to initially reduce speed and effect the turning and final stopping maneuvers. The requirement is made in both cases to be stopped relative to

the ground at a point about 3/4 n miles outside a 45° turn, in the presence of a strong wind and a flood current. For the first phase pilots were selected who, though familiar with the use of tugs, nevertheless do not use them conventionally during their daily routine operation. These are accomplished shiphandlers who rely on the use of engine power and rudder to accomplish their task. For the second phase, docking pilots were used. These are subjects who are highly accomplished in the use of tugs for maneuvering ships of all sizes as a daily routine but may not be as proficient in performing the same maneuvers without the tugs.

The experiment design is shown in Tables 2-1 and 2-2.

In Phase IA two groups of 8 subjects each on the 80,000 and 250,000 DWT ships respectively, performed the experiment with two tugs and four tugs "in attendance." These tugs though present were not to be used (inactive) unless a failure condition was encountered. The "inactive" tugs propel themselves at the same speed as the ship with lines slack, and consequently do not exert any appreciable increase in drag on the ship. The pilots were permitted to manipulate forward and/or reverse rpm for control and deceleration but were required to stop at the assigned point on the channel centerline between buoys 11 and 12. (Figure 2-1.)

The speed of the ships on entering the harbor from the sea outside (midway between buoys 3 and 4, Figure 2-1) was seven knots through the water in all cases along the centerline of leg 1. However the ship was not started in an equilibrium state for the existing wind and current. The pilot therefore had to overcome this initial perturbation

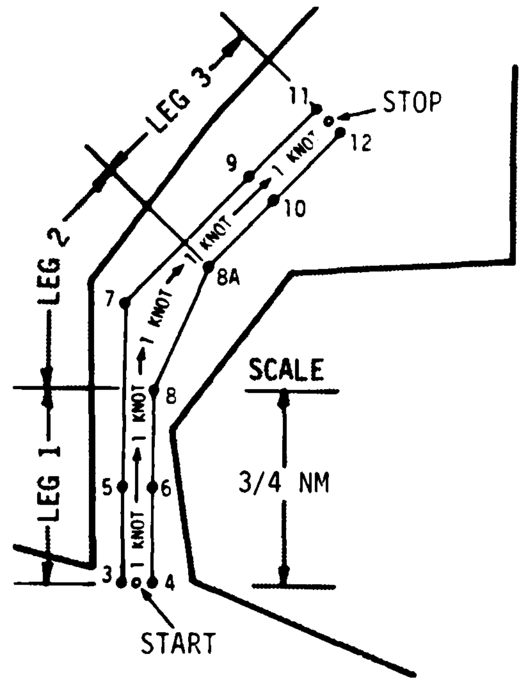


Figure 2-1. Harbor Configuration

on his ship. In order to follow the centerline as required.

A further group, Group 3, again on the 250,000 DWT ship consisted of 8 subjects, performed the same tasks but in this case the total available tug horsepower was 8,000 HP. This horsepower again was divided between either two or four tugs. These runs represented Phase IB and 2B of the experiment and were performed following the completion of Phase IA and Phase 2A.

In all cases the wind was gusting at 30 ± 10 knots and its direction varied ± 30° about the 315° point. The current was a following current of 1 knot strength, directed along the channel axis.

The three groups were given a familiarization run without wind and current; this was designed to acquaint

TABLE 2-1. EXPERIMENT DESIGN

Phase 1 - Tugs in Attendance But Inactive					
1A - 4,000 HP				1B - 8,000 HP	
Group 1 - 80K		Group 2 - 250K		Group 3 - 250K	
2 Tugs	4 Tugs	2 Tugs	4 Tugs	2 Tugs	4 Tugs
4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects
Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn	
Phase 2 - Tugs Active					
2A - 4,000 HP				2B - 8,000 HP	
Group 1 - 80K		Group 2 - 250K		Group 3 - 250K	
2 Tugs	4 Tugs	2 Tugs	4 Tugs	2 Tugs	4 Tugs
4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects	4 Subjects
Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn		Wind 30 ± 10 kn @ 315° ± 30 Current 1 kn	

1 Familiarization Run for Ship, Scenario - No Wind or Current
3 Replicate Runs
1 Complete Failure

TABLE 2-2. RUN ORDER

Phase 1 - Tugs in Attendance But Inactive**

4,000 HP Phase 1A				8,000 HP Phase 1B*	
Group 1		Group 2		Group 3	
80K 2 Tugs	80K 4 Tugs	250K 2 Tugs	250K 4 Tugs	250K 2 Tugs	250K 4 Tugs
S_1 - 2	S_5 - 5	S_9 - 6	S_{13} - 1	S_{33} - 3	S_{37} - 1
S_2 - 4	S_6 - 9	S_{10} - 11	S_{14} - 3	S_{34} - 4	S_{38} - 2
S_3 - 7	S_7 - 12	S_{11} - 15	S_{15} - 8	S_{35} - 6	S_{39} - 5
S_4 - 10	S_8 - 13	S_{12} - 16	S_{16} - 14	S_{36} - 8	S_{40} - 7

Phase 2 - Tugs Active**

4,000 HP Phase 2A				8,000 HP Phase 2B*	
Group 1		Group 2		Group 3	
80K 2 Tugs	80K 4 Tugs	250K 2 Tugs	250K 4 Tugs	250K 2 Tugs	250K 4 Tugs
S_{17} - 7	S_{21} - 2	S_{25} - 3	S_{29} - 1	S_{41} - 1	S_{45} - 4
S_{18} - 13	S_{22} - 4	S_{26} - 6	S_{30} - 5	S_{42} - 2	S_{46} - 5
S_{19} - 15	S_{23} - 9	S_{27} - 10	S_{31} - 8	S_{43} - 3	S_{47} - 7
S_{20} - 16	S_{24} - 14	S_{28} - 11	S_{32} - 12	S_{44} - 6	S_{48} - 8

* Phases 1B and 2B were begun after Phases 1A and 2A were completed.

** The run orders of Phases 1 and 2 are independent - The running of either phase is determined by the background of the test subjects available.

them with the ship characteristics, the scenario, navaids, etc.

Each subject in Phases 1A and 1B also made three replicate runs with tugs in attendance but always inactive, and finally experienced a complete failure at a designated point (in line with buoy 8), at which point the tugs could be activated. The complete failure represented a loss of engine power with the helm fixed amidships independent of rudder position prior to failure. If the failed rudder were not amidships as assumed here, the amount of tug usage and control effectiveness would depend on the amount and direction of the failed rudder. This type of failure compels the pilot to make full use of his tug support.

In Phases 2A and 2B, the experimental procedure was very similar - ship, wind and current conditions, and tug configurations. The three groups of 8 subjects apiece ran the initial familiarization run, and the three replicate runs with tugs actively in attendance. In this way the tugs could be used at anytime as desired to augment the rudder and rpm in control. These subjects also experienced a complete failure (in line with buoy 8) on their final run and modified their strategies to use tugs completely for control during the remainder of the passage.

The run order for the experiment is shown in Table 2-2. The order has been randomized for Groups 1 and 2, Phases 1A and 2A, and then for Group 3 in Phases 1B and 2B.

Performance measures derived from the output of these experiments were analyzed statistically using the Analysis of Variance, supplemented by Neuman-Keuls multiple comparison procedures. The various main and interactive effects are listed in Tables 2-7 and 2-8 and discussed in Section 3-2.

2.2 HARBOR DESCRIPTION

The simple channel configuration used in this experiment was identical to that used in a number of previous experiments. The spacing between buoys along the straight legs are uniformly 3/8 n mile. The channel is 800 foot wide along the straight legs and is widened in the turn to approximately twice this value. The scenario was designed to simulate to some degree the harbor situation existing at Pelican Island in Galveston, and the suggested sequence of tug procedures adopted here follows the recommendations of Senior Galveston pilots for Pelican Island.

The scenario presents an initial deceleration zone of 3/4 mile, Leg 1, (after entering from the ocean at buoys 3 and 4) during which the ship can be slowed down progressively to about 3 or 4 knots in which time tugs can pass towing hawsers and safely lash up alongside the ship. This is then followed by a 45° turn (which represents both the recommended maximum heading change acceptable in a harbor waterway, and also a smooth transition curve radius of at least five times the length of the biggest ship using the channel, Bonafous (1977)). On emerging from the turn, the ship can eventually slow down to stop midway between the gated buoys 11 and 12, three quarters of a nautical mile (or approximately four or five ship lengths) along this third leg.

The first two buoys, 3 and 4, mark the entrance from the ocean at which point tugs can begin to hook up. It is not until 5 minutes later that the tugs can be used effectively. This is based

on the previous assumption that on the average the pilots will reduce speed to 3 or 4 knots in leg 1. In practice it has been observed (National Ports Council, 1977) that tugs can complete making fast in 5 to 10 minutes, at 4 to 5 knots, even when up to six tugs are involved. With the highly maneuverable tugs in this experiment, the lower bound was chosen. The harbor is assumed completely sheltered so that wave action can be neglected and therefore not incorporated in the simulation. A surrounding land mass was added to provide more realism to the exercise. The starting and finishing points are shown in Figure 2-1.

The water depths inside the channel and outside have been chosen so that the depth/draft ratio of 1:15 is the same for both the fully loaded 80,000 DWT and the 250,000 DWT tankers used in this experiment. It was decided to select a constant depth/draft ratio for the two ships so that shallow water effects would be same for each. Had a constant depth channel been included these effects would be different due to the different drafts. The depth of water outside the channel section is adequate for safe operation of the selected tugs with their 9 foot draft.

The cross sections of the channels are shown below in Figure 2-2. These represent submerged channels and the relative dimensions of water depth inside (H) and outside ($H-H_1$, where ledge height = H_1) were selected so that the bank effect experienced by both ships would be about 38% of the bank effect they would individually experience in the presence of a fully emergent bank. This was determined based on Norrbin's reduction factor

$$\text{Reduction Factor} = e^{-2H_1/(H-H_1)}$$

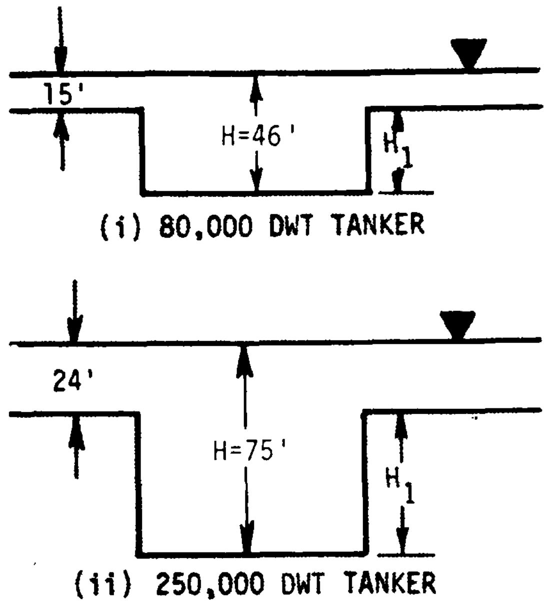


Figure 2-2. Channel Cross Sections

Consequently, with the present design, both the shallow water and bank effects should be comparable for both ships used in this experimental program.

2.3 ENVIRONMENTAL CONDITIONS

2.3.1 Wind. The wind in the harbor was assumed to be gusting with a strength of 30 ± 10 knots from the NW approximately (315° ± 30°). The time record of wind speed and direction is shown in Figure 2-3.

With the wind blowing from NW, the wind force will tend to decelerate the ship in the first leg, thus making it easier to slow down prior to the turn. However, luffing into the wind in the turn and in the final leg will make it more difficult to turn at low speeds,

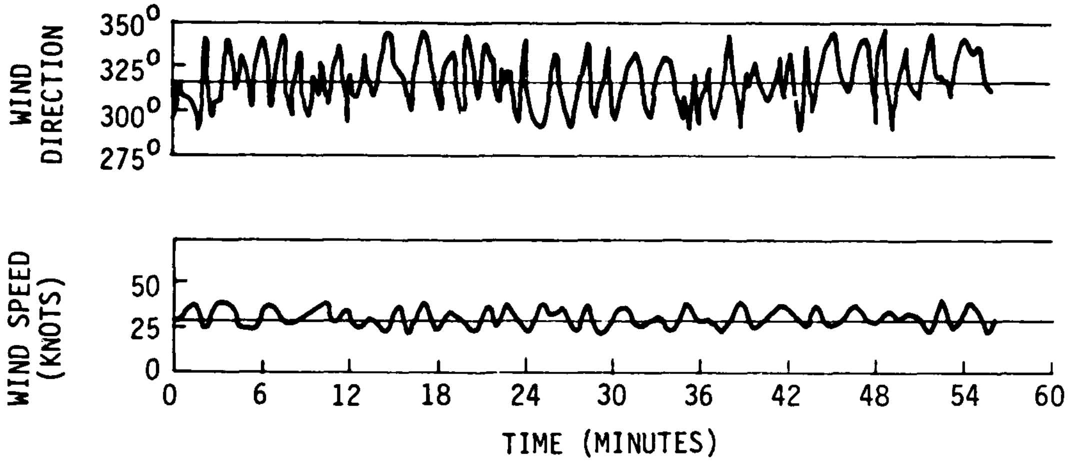


Figure 2-3. Time Variation in Wind Strength and Direction

and cause the ship to drift to starboard with its bow swinging to port as it decelerates. This will be accentuated by the presence of the following current.

2.3.2 Current. A flood current was assumed to flow in the channel direction at 1 knot speed. In the 45° turn it flows along the transition arc of radius 5,100 feet, which is tangential to the centerline of leg 1 and leg 2 at the buoy locations 8 and 8A respectively. The flow in the corner and at the cutoff were assumed to be separated and eddying and not contributing significantly to the overall water transport along the channel. On this basis, the current direction was changed in discrete steps to 7-1/2°, 22-1/2°, 37-1/2° and 45° at points A, B, C and D respectively as shown in the Figure 2-4.

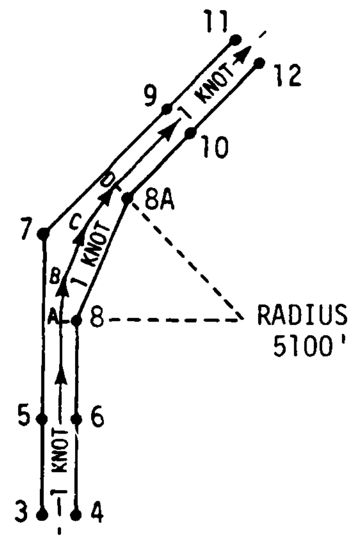


Figure 2-4. Current Intensity and Direction

2.4 SIMPLIFIED TUGBOAT SIMULATION

Three methods of attachment are possible:

1) Towing on line.
2) Pushing against the ship's hull.
3) Tugs lashed alongside.

A specific force is applied to Ownship in a specified direction relative to Ownship axis. The force input is designated as a fraction of the maximum bollard pull force available from the tug, according to the following

schedule, Table 2-3. This is assumed, based on sea-trial data, to be independent of ship speed (< 6 knots), section 2.5.1.

TABLE 2-3. TUG ENGINE SPEED/FORCE

Tug Order	Tug Force Function
Full Ahead	1.00
Half Ahead	0.50
Slow Ahead	0.25
Dead Slow	0.10
Stop	0

2.4.1 Attachment Points

The locations on Ownship's hull where the tugboats can be attached are defined in Figure 2-5. Three are located on each side of the ship, and one at the stem and one at the stern. The bow and quarter locations are one-third of a ship length forward and aft of the athwartship axis through the center of gravity. The location of the tug attachment point, when the tug is at the end of a towline, relative to the ship's centerline (y_{TRi}) is also listed in the simulation set up tape (SST). When the tug is alongside, y_{TRi} will be equal to 1/2 (ship beam + tug beam).

The maximum thrust ($TMAXF_i$) is the maximum value that can be applied by the given tug at the attachment point. The thrust direction ($TUGFPS_i$) is the direction of the applied thrust relative to the ship's axis, as shown in Figure 2-6.

The applied thrust is equivalent to the thrust force fraction (TFF_i) times the maximum possible thrust ($TMAXF_i$).

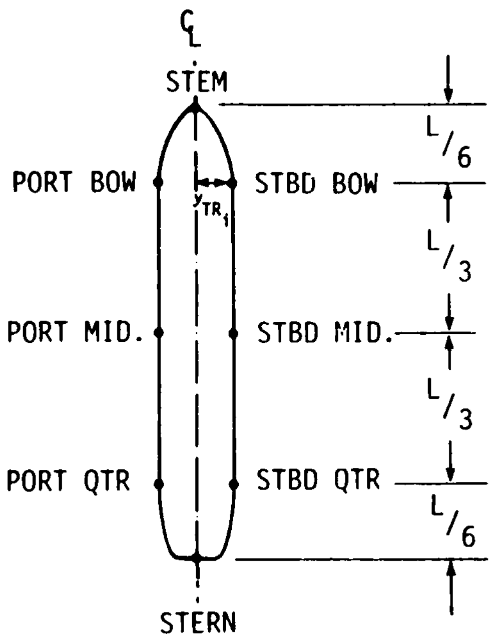


Figure 2-5. Notation for Tug Positioning

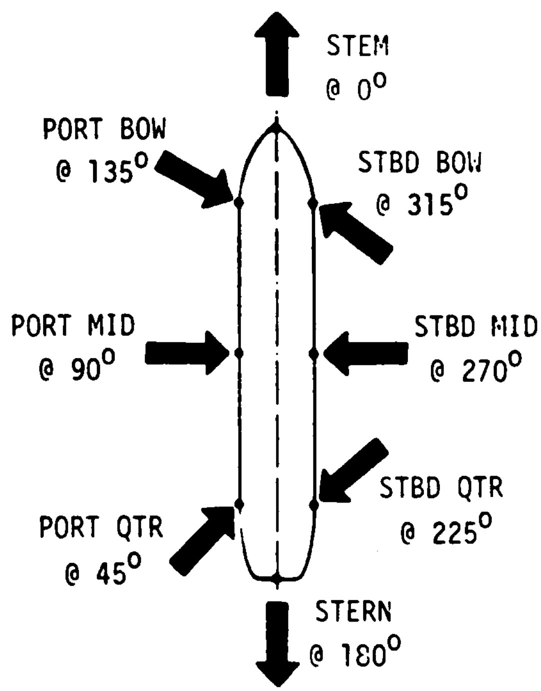


Figure 2-6. Convention for Tug Orders

Since there is a time delay between when the tug thrust and/or direction is commanded, and when it is actually attained by the tug, the model simply accounts for the variation, a linear build-up, in thrust and direction during this time period.

The commanded thrust, T_{C_i},

in direction $\psi_{C_i} = T_{max} C_i$,

where C_i = force fraction.

Then the time variation of thrust

and direction are

$$T_i = T_{(n-1)_i} + \alpha_1 (T_{C_i} - T_{(n-1)_i})$$

and

$$\psi_i = \psi_{(n-1)_i} + \alpha_2 (\psi_{C_i} - \psi_{(n-1)_i})$$

when $0 \leq \alpha_1 \leq 1$ and $0 \leq \alpha_2 \leq 1$;

Thereafter $T_i = T_{C_i}$ and $\psi_i = \psi_{C_i}$

The dimensionless time factors α_1 ($= \Delta t/\tau_1$) and α_2 ($= \Delta t/\tau_2$) are derived from the time in seconds that has passed since the order was inserted in the simulator (Δt) and the corresponding time constants τ_1 ($PROPTC_i$) and τ_2 ($TFDTC_i$) for thrust and direction, respectively, in seconds.

An active tug will consequently interact with Ownship in the specified mode (thrust and direction) and at the assigned attachment point as specified above.

For tugs lashed alongside, the effective lever arm for determining the moment on the ship is 1/2 (ship beam + tug beam). Relative to the ship length this fraction is denoted by BT_i in the simulation.

The forces and moments resulting from the tugs are, for each tug:

$$X_{t_i} = T_i \cos \psi_i$$

$$Y_{t_i} = T_i \sin \psi_i$$

and $N_{T_i} = Y_{t_i} l_{t_i} - X_{t_i} (B/2)$

where l_{t_i} = distance of tug i from the ship's center of gravity measured along the centerline of the ship.

For a tug pulling on a towline the moment will be

$N_{t_i} = Y_{t_i} l_{t_i} - X_{t_i} y_{tR_i}$, rather than the above.

The total forces and moments exerted by the tugs on the ship are simply the addition of the individual contributions.

Since the subjects tend to issue orders with tugs pushing or pulling at the starboard and port positions perpendicular to the centerline of the ship, it is convenient for the control station operators to insert directions of 270° and 90° respectively, and then use positive and negative values for the thrust fraction for pushing and pulling. For example, a full ahead thrust at starboard bow corresponds to a positive thrust factor of one and 270° direction. On the other hand, a full astern pull at the same point corresponds to a negative thrust factor of minus one, but with the same direction.

2.5 OWNSHIP AND TUG CHARACTERISTICS

Two fully loaded tankers were used as Ownship in these experiments. They represent a large ship of tonnage

familiar to most pilots in US ports (80,000 DWT), and one of a very large tonnage that is familiar to only a few pilots (250,000 DWT). Their characteristics are tabulated in Table 2-4.

For both these ships the following simulations were available and were used during these experiments:

1) Zero/low speed hydrodynamics.
2) Aerodynamics.
3) Shallow water effects.
4) Bank effects.

However, squat and modified trim in restricted shallow waters and wave forces (all of which would be small in this scenario) were not included in the simulation.

2.5.1 Tug Simulation

For the present experiments the "simple" tug simulation procedure was used since the advanced tug simulator was not available until later. Fortunately the assumptions implied in using this simplified form (constant thrust and angle of application independent of ship speed, tug capabilities, etc.) could be used with some confidence based upon the results of the sea-trials involving the "Tina" (a 1,000 HP tug with 360° steerable propulsion units and Kort nozzles) and the 25,000 DWT USNS "Yukon." These tests were performed to measure static and dynamic bollard pulls at angles to the ship's centerline while the ship and tug were proceeding at speeds from zero to six knots. In addition the tug's effectiveness when trailing and pulling with astern thrust was assessed. An examination of the data indicated that if a maximum bollard pull of a constant 27,000 pounds were adopted independent of ship speed (but less than 6 knots), hawser angle and propulsion unit angle, the maximum error would never exceed 10%. Such an assumption was ideal for our purposes, and consequently tugs with "Tina's" characteristics were built into the present experiment. In addition, this same tug with its hydrodynamics and aerodynamics etc. was to be used initially in the advanced tug simulator. During the initial verification and validation phases of this advanced tug model the

TABLE 2-4. OWNSHIP CHARACTERISTICS

	250K DWT	80K DWT
Length (L)	1,085 ft.	763 ft.
Draft (T)	65 ft.	40 ft.
Beam	170 ft.	125 ft.
Depth/Draft	1.15	1.15
Ahead HP	36,000	24,000
Prop. Dia.	29.2 ft.	25 ft.
Max. Rudder Angle	35°	35°
Rudder Area (A_R)	1,302 ft.^{2}	517.5 ft.^{2}
Rudder Area Ratio (A_R/LT)	0.018	0.017

appropriateness of the simple model used here would become apparent. The characteristics of the "Tina" tug are tabulated below in Table 2-5.

These tugs can contribute maximum thrusts of the order of 27,000 pounds on a continuous basis at any heading and hence, without the tug having to be repositioned, control of Ownship can be maintained at all times. Full thrust can be obtained aft and broadside as well as forward, which permits a minimum amount of line handling while docking.

The magnitude of horsepower to be assigned to the tugs in this experiment was determined after closely examining literature dealing specifically with actual tug operations throughout the world (e.g. National Ports Council, 1977).

There appeared to be an extremely wide variation in specifications for the required total tug horsepower as related to ship size. Based on the available information, and a formula based on testing at NMI in the UK, a total bollard pull of 50 tons was considered appropriate for the maneuvers in this experiment. This value could be achieved by using either four 1,000 HP or two 2,000 HP tugs of the "Tina" type. As a consequence, these tug types were incorporated in the present design.

When two tugs were used in the present experiment, they could either be attached at the bow and the stern on soft lines, or be free to push against the ship hull at attachment points initially assigned by the pilot on first entering the channel. When four tugs are employed, they were free to operate on lines or in the pushing mode at points assigned by the pilot.

In order to simulate real world conditions more realistically in these experiments a five minute time delay was imposed after entering the channel before the tugs could become effective. In addition, for a tug attached at a given point on the ship there was a time delay of one minute between the

TABLE 2-5. CHARACTERISTICS - WILMINGTON LAUNCH TUG TINA

Length Overall	65.0 ft.
Beam, Molded	26.0 ft.
Draft, Molded	9.0 ft.
Draft to Bottom of Skeg	10.5 ft.
Displacement (Design), tons	127.5
Brake Horsepower	1,000 HP

Propulsion. Two diesel engines coupled to Murray and Tregurtha 360-degree steerable propulsion units with propellers in Kort nozzles. The two propellers are mounted aft. The tugboat is designed to operate as a tractor tugboat when going astern.

Propellers. Right-hand, four-bladed, Kaplan type; 5.33 feet diameter in a Kort nozzle.

time an order is given by the pilot and when it is effectively carried out by the tug (i.e. τ_1 = 60 secs). If a tug is moved from one attachment point to another on the opposite side of the ship a further 2 minute delay occurred; if moved from one attachment point to another on the same side, this delay was one minute.

2.5.2 Tug Display

During the simulation exercise the pilot was at a disadvantage in that he could not check tug locations by peering out of the wheelhouse. Therefore he must remember which tugs were active and which were inactive, as well as at what power levels they were operating. To compensate for this deficiency the pilot was presented with a display of the ship's planform and the relative tug positions using a closed-circuit TV monitor, Figure 2-7.

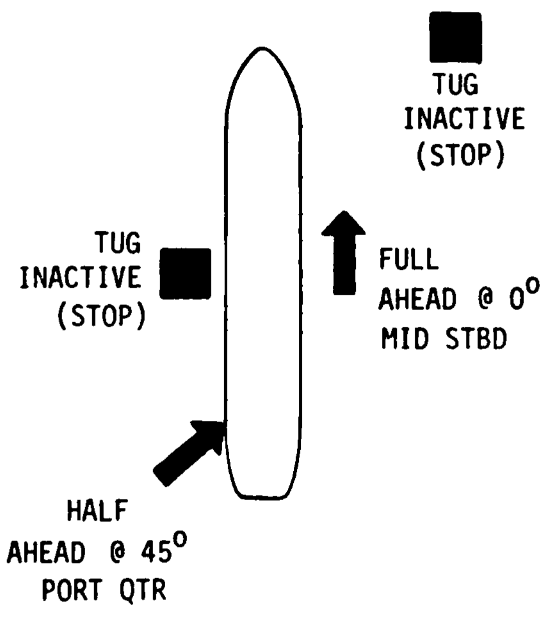


Figure 2-7. Tug/Ship Configuration as Displayed to Pilot

At the control station a white magnetic board, approximately 2 ft. x 1-1/2 ft., had a black planform of the ship superimposed. In addition, active tugs were represented by black arrows with the arrowheads indicating the direction of thrust. If the tug were on a towline, the arrow would be displaced from the ship hull; if it were alongside or pushing, the arrow would be adjacent to or abut the hull. The angle of application of thrust was shown by the arrow's direction.

"Inactive" tugs were represented by small black magnetic squares, situated approximately in their last active positions relative to the ship. These arrows and squares were moved by one of the control operators when the pilots' orders were carried out at the control station.

The pilot was also provided with a diagram indicating the tug attachment points that are available (Figure 2-5), in addition to the proposed format for commanding tug forces and directions (Figure 2-6). This format was discussed with the pilot prior to his runs. At the same time he also explained his personal conventions for issuing orders, so that an accurate interpretation could be made by the control operators.

Engine orders were performed in the telegraph mode.

2.6 TEST SUBJECTS

The forty-eight pilots who participated in this experiment were drawn from essentially three different areas of the East Coast of the United States, and comprised both harbor pilots and docking masters. The former who were assigned to Groups 1, 2 and 3 in Phases 1A and 1B, came from New York (9), Boston (7),

Delaware (7) and the St. Lawrence Seaway (1). The latter group assigned to Groups 1, 2 and 3 in Phases 2A and 2B hailed from New York (13), Boston (7), Delaware (2), and Houston (2).

2.7 PRELIMINARY OPERATIONS

Before performing his experimental runs, the pilot was briefly introduced to the CAORF bridge and its equipment, the properties of the visual scene and the specific procedures that would be used. A large number of the subjects, including all of the docking pilots involved in Phases 2A and 2B, had never been exposed to CAORF before. A mate (a member of the CAORF Operations staff) was present to respond to any questions the pilot might have concerning the ship. The pilot was shown the signal telegraph control and informed that bridge control would be used during the experiment; his engine orders would be executed by his mate, who would also monitor and record his helm and tug orders during the experimental runs.

The pilot was then briefed by a member of the CAORF staff who discussed the scenarios, channel dimensions, banks, shallow water, winds and currents, ship and tug characteristics, operating procedures and requirements. He was then provided with a chart of the harbor and a detailed printed booklet duplicating the details of the verbal briefing. The pilot could therefore refer to this document and chart at any time during the experiment should he have any questions. He was told he would perform five runs in all, the first for familiarization and subsequent runs for improvement of techniques. He was not told at any time to expect a complete mechanical failure.

The first of his experimental runs (Run 1) was designed to familiarize the pilot with the harbor scenario, the navaids and the ship which he would use throughout his series of runs. During this familiarization run, performed in the absence of external environmental influences, the objectives were identical to the following runs; namely to be stopped relative to ground at the end of leg 3.

At the end of each run a short informal briefing was held with each subject by a member of the CAORF Research staff. Questions regarding the subjective reactions to the run, vessel handling, wind and bank effects, tug handling qualities, etc., were explored.

At the end of the series of five runs a final debriefing session was held to obtain an overall assessment of the experiment from the pilot and indications of where in his judgement certain aspects may have lacked realism.

2.8 DATA COLLECTION

A variety of sources were used for data collection during the running and analyses of the experiment. The major performance measures were obtained or derived from computer summary datalogs, ship's bridge data sheets, and debriefings. The primary source for all objective data during the actual experiment runs was the "playback tape." This is a magnetic recording of each run, taken at a fixed time interval, of important computer and ship state parameters (numbering well over 1,000 items). The recording rate for the experiment was once every 10 seconds.

2.9 COMPUTER SUMMARY DATALOGS

Computer summary datalogs are printouts from the playback tapes. This

information was made available as hard copy printouts at the end of groups of runs. A listing of the 46 items obtained on the printouts and used in the subsequent analyses is shown in Table 2-6.

2.10 DATA PRESENTATION

Data collected during the experiment are presented in the following format for visual interpretation and qualitative evaluation that will complement

TABLE 2-6. COMPUTER SUMMARY DATALOGS

IDENTIFIER	Playback Tape Number
TIME	Time Step Number Bridge Time (hr:min:ss)
HYDRODYNAMICS	X-Axis Hydrodynamic Hull Force (lb/10) Y-Axis Hydrodynamic Hull Force (lb/10) Hydrodynamic Moment (lb-ft/10)
WIND	Actual Wind Speed (knot) Actual Wind Direction (degrees) Aerodynamic Force X-Axis (lb/10) Aerodynamic Force Y-Axis (lb/10) Aerodynamic Yaw Moment (lb-ft/10) Relative Wind Direction (degrees) Relative Wind Speed (knots)
DEPTH	Water Depth
O/S SPEEDS	O/S Heading (degrees) O/S Fore & Aft Speed (ft/sec) O/S Athwartship Speed (ft/sec) O/S Velocity North (knot) O/S Velocity East (knot) O/S Ground Speed (knot) O/S Resultant Speed (ft/sec)
BANK EFFECTS	O/S Centre Distance to Bank/Channel (nm) Channel/Bank Interaction Y Force (lb/10) Channel/Bank Interaction Moment (lb-ft/10)
WATER CURRENT	Water Current Speed, Checkpoint 1 (ft/sec) Water Current Direction, Checkpoint 1 (degrees) Water Current Speed, Checkpoint 4 (ft/sec) Water Current Direction, Checkpoint 4 (degrees)
O/S LOCATION	O/S North Coordinate (nm) O/S East Coordinate (nm) O/S North Bridge Coordinate (nm) O/S East Bridge Coordinate (nm)

TABLE 2-6. COMPUTER SUMMARY DATALOGS (CONT)

PROPELLER	#1 Engine Propeller Revs (rpm) #1 Engine X-Axis Propeller Force (lb/10) #1 Engine Y-Axis Propeller Force (lb/10) #1 Engine Propeller Moment (lb-ft/10)
RUDDER	Rudder Angle (degrees) Rudder X-Axis Force (lb/10) Rudder Y-Axis Force (lb/10) Rudder Yaw Moment (lb-ft/10)
SHIP ACCELERATIONS	O/S Fore/Aft Ship Acceleration (ft/sec^2) O/S Athwartship Ship Acceleration (ft/sec^2) O/S Yaw Acceleration (radian/sec^2)
COMBINED NON-HYDRO EFFECTS	X-Axis Combined Forces (non-hydro) (lb/10) Y-Axis Combined Forces (non-hydro) (lb/10) Combined Moment (non-hydro) (lb-ft/10)

the conclusions of the statistical analyses of the same data.

- o Ship track plots, derived from the ship's dimensions, the coordinates of its center of gravity (X_o, Y_o) and its heading as recorded in the data summary at two minute intervals.

  This was done for 48 runs, and is presented in two groupings:

  1) Familiarization (Run 1) and the three subsequent replicate runs per subject, and

  2) Failure runs (Run 5) of all subjects.

- o Simultaneous plots of rudder angle, rudder moment and engine speed variation with time over the duration of runs, for both the active and inactive tug modes. These data are obtained directly from the data summary. For the active mode these quantities are shown along with the corresponding plots of tug forces X_T and Y_T and tug moment N_T.

- o Simultaneous plots of tug forces and tug moments for the active tug mode and also for all 48 failure runs. The data for these plots were derived from the information on combined non-hydrodynamic forces and moments (due to wind, banks and tugs) and the individual values for wind and banks. Since the tug values obtained in this way usually involved the subtraction of large numbers, errors arose which indicate the existence of small tug forces and moments in the inactive mode where in fact they should be exactly zero. In the presentation of Anova data these small errors have been identified.

- o Plots indicating the mean distance off the assigned track (the centerline in legs 1 and 3, and the transition arc in leg 2) at 400 feet intervals. The individual

values of distance off track were calculated from the ship coordinates at the interpolated time corresponding to each 400 foot increment using the information in the data summary. The data corresponding to the subjects in each combination of factors considered, for example, ship size, tug mode and tug number, were then averaged to obtain the mean distance off-track at that location. At the same time the standard deviation and the extremes of these individual measurements were estimated. The mean, standard deviation and the extremes are all depicted on the plots. The extent of each leg is indicated on the horizontal axis, where for convenience the circular arc has been straightened. It should also be noted in these plots that the actual channel width in leg 2 is greater than the nominal 800 feet in each of the other legs. The variation in width is shown in Figure 3-9 and should be taken into consideration when visually evaluating the closeness to grounding.

2.11 NEW PERFORMANCE MEASURES

Performance has conventionally been measured in terms of the RMS deviations off an assigned track and the RMS rudder angle that was used. The RMS deviation off-track of the ship's center of gravity, however, must be considered in conjunction with the swept path to indicate the closeness of the ship's extremities to the channel boundaries. In itself it does not give a measure of the nearness to grounding. The RMS rudder angle indicates the amount of rudder that was used to perform the transit, and consequently the amount of rudder that remains to control the ship should an emergency situation arise. Again this measure in itself is not sufficient. The amount of rudder moment that can be exerted by the ship is dependent not only on the amount of rudder but also the rudder efficiency; the rudder efficiency is a function of hull speed *and* engine speed, and importantly the direction of propeller rotation. This is demonstrated very clearly in the time histories of rudder moment, rudder angle and engine RPM (Figures 3-2 and 3-3). In these figures it can be seen that in the final deceleration stages of leg 3, the engine is going full astern and the rudder angle is saturated. However, due to the ship's low speed the actual rudder moment is very small compared to its values at prior times. That is, as the ship decelerates, it effectively loses all its rudder control efficiency. It would therefore be more realistic to adopt a performance measure of RMS rudder moment or RMS "effective" rudder angle to account for not only actual rudder angle but also the ship's hull speed and engine speed during the transit. As a consequence of these considerations a new concept of a combined performance measure was adopted to account for the interaction of all the ship's state and control variables. This new measure or performance index will be denoted by J and will contain

a) effect of rudder and deviation off-track
b) "inherent" risk
c) tug moment

(a) The contribution of rudder is the mean value of the sum of the squared rudder angles normalized with respect to the maximum rudder angle, 35°. That is,

$$^{1}/_{T} \int_{o}^{T} (^{\delta}/_{35})^2 \, dt, \quad \text{or}$$

$$(^{\delta RMS}/_{35})^2$$

Similarly, the contribution of deviation off-track is the sum of the squared deviations normalized with respect to a bias value of 100 feet. It was considered that pilots would be quite satisfied with their performance if their ship lay within 100 feet either to the left or right of the designated track, and would not necessarily make any effort to return the ship exactly to the track. Especially in the presence of wind they may prefer to lie to windward. The subsequent experiment tended to justify this value.

Hence deviation off-track contribution

$$= {}^{1}/_{T} \int_{0}^{T} ({}^{y}/_{100})^2 \, dt \quad \text{or}$$

$$({}^{y_{RMS}}/_{100})^2$$

These two contributions to J do not tell the complete story, for they indicate that a low value of the performance index, indicating good performance, can be achieved by travelling at higher speeds. Higher ship speeds increase the rudder efficiency, decrease the rudder angle requirement, minimize the wind influence and produce better trackkeeping. However, this does not consider the possibility of mechanical (rudder and engine) failures taking place at any time. In this case, it would be preferable to be travelling at low speed, contrary to the above conclusion! To include the possibility of a failure at any point along its track and the "inherent" risk of grounding, the following concept was developed.

(b) The vulnerability of the ship at any instant is a function of the state and the actual position of the ship -- its location, heading, turn rate, speed, its dimensions *and* the contours of the boundaries of the waterway. In the event of a rudder and/or engine failure, the time ("recovery time") before the failure can be corrected, or before the tugs can restore the ship to follow a safe track and prevent grounding is an extremely important factor. In the subsequent analysis three values for recovery time were assumed -- 2-1/2, 5 and 10 minutes respectively.

From the state of the ship and its position at each time interval during the passage the velocity and direction of the stern and the stem were calculated assuming, for simplicity, that the ship may be represented as a straight line. This assumption can be easily corrected to account for the ship's actual hull form. Now assuming that the ship's speed and direction remain unchanged following the failure its trajectory can be calculated and the shortest time for the first impact on the surrounding boundaries estimated. In this way the "inherent risk" of grounding can be established. If the time for the ship to strike the nearest boundary is less than the recovery time then a grounding will take place and a value of unity will be assigned for this time. Conversely, if the impact time is greater than the recovery time a zero value is assigned to the risk. In this way corresponding to each point along the ship's trajectory a value can be assigned, either 0 or 1, which are then accumulated in time. The ratio of the number of grounding possibilities and the total time in the channel section represent the percentage of time the ship is in danger of grounding should a failure occur. This has been denoted in the subsequent analysis by α_1, α_2, or α_3 (depending on the values assigned to the recovery time). This is an important addition to the performance index as it is speed dependent. Even when the ship is perfectly on track, there is always an inherent risk if the speed exceeds a certain limit when negotiating turns in restricted waterways.

This is illustrated by a simple calculation (Appendix C) which shows that in the present scenario the inherent risk in the turn is zero only if the speed is maintained at 3 knots or lower (based on a five minute recovery time).

When tugs are also being used for controlling the ship, the state and position of the ship is dependent on the prior tug usage. However, any assistance from the tugs following a failure is not accounted for in the calculation of α. Some time will elapse before they can effectively divert the ship's path, and their effect on inherent risk will be principally in reducing the recovery time. Sample off-line calculations (Appendix B) demonstrate the influence of instantaneous tug assistance on the advance and transfer of the ship following failure.

(c) When tugs are being actively used for controlling the ship, an additional tug contribution is added to the performance index, namely $(\text{RMS } N_{TUG}/N_{MAX\ TUG})^2$. This is similar to the rudder contribution, and represents the degree to which tugs are being used in controlling the ship relative to their full potential. Similarly it also provides a measure of the amount of tug moment remaining that is available when needed.

The maximum tug moment is produced when half the tug power is applied at the forward attachment point (1/3 length ahead of the center of gravity) and the other half at the aft attachment point (1/3 length behind the center of gravity) but in the opposite direction. For the tug used in this study a maximum bollard pull of 27 lb. per tug BHP was used. Consequently if P = tug horsepower

$$N_{TUG\ MAX} = 9\ PL.$$

Only tug moment was included in the performance index since we are mainly concerned with control. No consideration has been given to the lateral and longitudinal forces that produce these moments, but which in themselves play an important role in maintaining the ship on a safe track, particularly during the final deceleration stages of leg 3.

The final representation of the performance index J used in the subsequent analysis is

$$J_L = \alpha_i + \left(\frac{Y_{rms}}{100}\right)^2 + \left(\frac{\delta_{RMS}}{35}\right)^2 + \left(\frac{N_{TUG\ RMS}}{N_{MAX}}\right)^2$$

where index i (=1, 2, 3) refers to the assumed recovery times (2-1/2, 5, 10 minutes) respectively.

2.12 ANOVA ANALYSIS

The statistical analysis of the overall experiment which consisted of two basic parts was carried out using the Analysis of Variance (ANOVA) on each of the performance measures under consideration.

Anova 1. The first basic analysis considers the effect of ship type (A) (80,000 DWT, 250,000 DWT) when the total available tug horsepower is fixed at 4,000 BHP. This comprises information from Groups 1 and 2 of Phases 1A and 2A.

Anova 2. This second analysis considers the effect of total tug horsepower (4000, 8000 BHP) when the ship is fixed, i.e., the 250,000 DWT tanker. This comprises all the information from Group 2 in Phases 1A and 2A, along with that from Group 3 in Phases 1B and 2B.

These Anova's were performed for each of the twenty-three measures listed below. Tables 2-7 and 2-8 show the resulting main analysis source tables. They indicate the significant main effects and interactions (up to the fifth order) to significance levels of $p = < 0.001$, < 0.01 and < 0.05 respectively denoted by the cross, circle and square in these charts. Not all measures are discussed in detail in this report.

The independent variables are defined as follows:

A = Ship Type (80,000 DWT or 250,000 DWT)

B = Tug Number (2 tugs or 4 tugs)

C = Tug Mode (Active or Inactive)

D = Replicate Run Number (Run 2, Run 3 or Run 4)

E = Leg Number (Leg 1, Leg 2 or Leg 3)

H = Horsepower Levels (4000 and 8000 HP)

The analyses are performed only on the data obtained from the three replicate runs. The familiarization (first) run and the failure (fifth) run were examined separately and more subjectively.

The performance measures investigated were:

- o % time for left rudder*
- o % time for right rudder*
- o Total time the rudder was used
- o % time engine in forward RPM
- o % time engine in reverse RPM

* Left and right rudder contributions were only considered if $|\delta| > 3^o$, as smaller angles (jitter) can be attributed to the helmsman and do not contribute to the ship control. Similarly engine RPM values between $\pm$ 5 RPM are also omitted in estimating the times.

The total time during which rudder was used is the mean value per leg, i.e., the total time during the complete transit divided by three (three legs).

- o % Time ship lies to left of designated track**

  ** The designated track is the centerline of leg 1 and leg 3, and the 5,100 foot radius arc in the turn (leg 2).

- o % Time ship lies to right of designated track
- o Perpendicular distance off the designated track
- o RMS Rudder Angle (degrees)
- o Mean Swept Path (ft)
- o Total time in leg (minutes)
- o Performance Index J_1
- o Performance Index J_2
- o Performance Index J_3
- o Risk Factor α_1
- o Risk Factor α_2
- o Risk Factor α_3
- o Contribution of distance off-track to J

  $$= \left(\frac{Y_{RMS}}{100}\right)^2$$

- o Contribution of rudder to J

  $$= \left({}^{\delta RMS}/_{35}\right)^2$$

TABLE 2-7. SOURCE TABLE - ANOVA 1 - SHIP COMPARISON

PERFORMANCE MEASURE	C	A	B	D	E	CA	CB	AB	CD	AD	BD	CE	AE	BE	DE	CAB	CAD	CBD	ABD	CAE	CBE	ABE	CDE	ADE	BDE	CABD	CABE	CADE	CBDE	ABDE	CABDE
% TIME LEFT RUDDER		x			x								○																		
% TIME RIGHT RUDDER				□									○						□												
TOTAL TIME RUDDER/LEG				x	x					□																					
% TIME FORWARD RPM		x			x	□	x						○			x		□													
% TIME REVERSE RPM		x			x	□							○							○											
TOTAL ENGINE TIME/LEG		x		□	x		x			x			○		□			□						□				□			
TIME TO LEFT OF C																			□												
TIME TO RIGHT OF C																			□												
RMS RUDDER		x	○	x	x								○																		
SWEPT PATH		x	○	○	x								□		□					○											
TOTAL TIME IN LEG		□		x	x					x		□	x		□	□	○							□				○			
FUNCTION J_1			x	□	x									○									□								
FUNCTION J_2		□	○		x									○									□								
FUNCTION J_3			○	□	x					□				○																	
RISK FACTOR α 1					x								□																		□
RISK FACTOR α 2		x		□	x					□			x	□	○									○							
RISK FACTOR α 3		x			x																										
DEV. OFF-TRACK CONTRIB.			□		x					□				○					□				□	□							
RUDDER CONTRIBUTION		○	□	x	x								○																	□	
TUG MOMENT CONTRIBUTION	x	x	○		x	x	○	x				x	x			x				x											
MEAN SPEED IN LEG		○			x								x		○		□														
RMS YAW RATE					x					□					○														□		
RMS COURSE ERROR					x																								□		

C = TUG MODE (ACTIVE/INACTIVE)
A = SHIP TYPE (80,000 DWT/250,000 DWT)
B = TUG NUMBER (2/4)
D = RUN NUMBER (2, 3, 4)
E = LEG NUMBER (1, 2, 3)

○ $p < 0.001$
x $p < 0.01$
□ $p < 0.05$

TABLE 2-8. SOURCE TABLE - ANOVA 2 - HORSEPOWER COMPARISON

PERFORMANCE MEASURE	SOURCE																														
	C	H	B	D	E	CH	CB	HB	CD	HD	BD	CE	HE	BE	DE	CHB	CHD	CBD	HBD	CHE	CBE	HBE	CDE	HDE	BDE	CHBD	CHBE	CHDE	CBDE	HBDE	CHBDE
% TIME LEFT RUDDER					×																										
% TIME RIGHT RUDDER					○						□																				
TOTAL TIME RUDDER/LEG				□	×																										
% TIME FORWARD RPM				□	×	○										×															
% TIME REVERSE RPM		□			×	○							□							○											
TOTAL ENGINE TIME/LEG					×											□			□												
TIME TO LEFT OF C		□						□														□									
TIME TO RIGHT OF C		□						□														□									
RMS RUDDER				□	×																										
SWEPT PATH				□	×		□								□						□						□				
TOTAL TIME IN LEG				○	×										□	○	□							□			○	○			
FUNCTION J_1					×																						□				
FUNCTION J_2					×																										
FUNCTION J_3					×																										
RISK FACTOR $\propto 1$					×																										
RISK FACTOR $\propto 2$					×														□		□										
RISK FACTOR $\propto 3$					×			○														○									
DEV. OFF-TRACK CONTRIB.					×																										
RUDDER CONTRIBUTION				□	×																										
TUG MOMENT CONTRIBUTION	×	×			×	×		×				×	○			×				○		□					□				
MEAN SPEED IN LEG					×											○	□											□			□
RMS YAW RATE					×																										
RMS COURSE ERROR					×																										

C = TUG MODE (ACTIVE/INACTIVE)
H = TUG HORSEPOWER (4000/8000)
B = TUG NUMBER (2/4)
D = RUN NUMBER (2, 3, 4)
E = LEG NUMBER (1, 2, 3)

○ $p < 0.001$
× $p < 0.01$
□ $p < 0.05$

- Contribution of tug moment to J

  $$= \left(\frac{N_{TUG\ RMS}}{N_{TUG\ MAX}}\right)^2$$

- Total number of points in leg (corresponding to time in the leg)
- Mean longitudinal speed in leg (ft/sec)
- RMS Rate of Turn (radians/sec)
- RMS Course error (radians)***

*** In the turn the error is referred to the tangent to the arc; in the first and third legs it is referred to 0° and 45° respectively.

CHAPTER 3

RESULTS AND DISCUSSIONS

The data collected during this investigation were examined in two ways: qualitatively by visual examination of simultaneous plots of ship tracks and corresponding controls, and quantitatively by statistical methods.

3.1 QUALITATIVE ANALYSES

This section describes the results of the qualitative approach. The statistical approach is discussed in Section 3.2.

3.1.1 Observations on Non-Failure Runs

There were two distinct techniques used when making the 45° turn from leg 1 into leg 3. The first was to cut across the inside edge of the turn parallel to the line connecting buoys 8 and 8A. In this way ship heading variation with time could be represented as in Figure 3-1a, that is, maintaining a constant heading of about 22-1/2 for the major period of time. The second was to follow a curved path with a nearly constant turn rate, closely approximating the 5100 foot radius arc used in the analyses as the designated track. In this case the ship heading-time variation appears as in Figure 3-1b.

The first technique prevailed in the (first) familiarization run where the disturbing influence of wind and current were absent and the exercise was relatively easy. However in a few instances troubles were experienced in controlling the basic ship around the turn. In some cases the technique changed from the first to the second in the learning process during run replication.

From these track plots there does not seem to be any significant difference in the outcome of the techniques employed by the harbor pilots and by the docking masters (that is, the inactive mode versus the active mode.)

In the presence of the wind and the current, the final deceleration stage proved to be the critical phase where tug assistance was most important. Without tugs the ship tended to drift to the right boundary of leg 3 and at

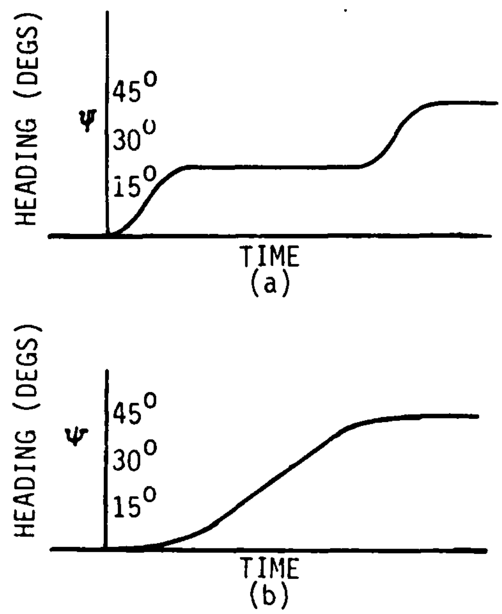


Figure 3-1. Turn Strategies
(a) Constant Heading
(b) Constant Turn Rate

the same time luffing into the N.W. beam wind (counterclockwise rotation). With the engine running in reverse to produce the required deceleration, the rudder became extremely ineffective at the low hull speeds (as discussed in Section 2-11). As a consequence, during the final deceleration phase the ship lost its capability to resist the wind forces and moments almost completely. This is the time when the tugs can be employed most effectively.

In the case of the harbor pilots (Subjects 1-16 and 33-40) examination of Figures 3-2A through 3-2D indicates that there was a wide variation in techniques used in shiphandling -- periods of constant rudder, rudder magnitudes and frequency, engine speed variations, periods of forward and reverse RPM, periods when the engine is stopped, the use of the kick effect (apparent from the sharp spikes in the rudder moment curves and engine RPM), etc. The docking masters exhibited similar variations in techniques of basic shiphandling, and even though they had tugs available they still preferred to use rudder and engine RPM solely for control until the later stages of their transit.

Of the 24 docking master (subjects 17-32, and 41-48) there were only five who actually used their available tugs in making the 45° turn (leg 2), Figures 3-3A through 3-3H. Of these five, two used them principally for decelerating the ship, the others for control (lateral force and moment). In general, tugs were not used to any extent until the final phase of leg 3 and then for deceleration and/or low speed control under disturbing influence of the wind and current.

3.1.2 Ship Ground Tracks

Ship ground tracks that show the ship planform and the position of the rudder at two minute intervals are presented in Figures 3-4A to 3-4X for all 48 subjects. They are grouped to show the results of the familiarization run (Run 1) followed by the three replicates (Runs 2, 3 and 4). In this way it is possible to conveniently examine the tracks for any subject or subjects to discern any differences in techniques with replication. The results of the fifth (failure) runs appear in Figures 3-5A through 3-5 F and these are also grouped so that ready comparisons can be made. Each page of the failure run plots corresponds to the tracks for eight subjects in each group and each phase of the experiment, four of whom had two tugs assisting and the other four had four tugs of the same total horsepower.

3.1.3 Rudder Angle, Engine RPM and Rudder Moment

For the penultimate run of each subject, representing his final replicate, plots are presented in Figures 3-2 and 3-3 showing the time variation of rudder angle used, the engine rpm and the rudder moment. Figure 3-2 shows this data for Subjects S1 to S16 and S33 to S40, who had tugs in the inactive mode which consequently were never used until the final run. The extent of legs 1, 2 and 3 are indicated on the horizontal time scale.

Examination of these plots gives an insight into the techniques used by each pilot in controlling the ship -- the magnitude and frequency of rudder, the use of engine speed for control, and the effectiveness of his rudder at

Note: Figures 3-2A through 3-8C will be found on pages 3-15 through 3-68.

various stages of the transit. Figure 3-3 on the other hand, shows not only rudder angle, engine RPM and rudder moment, but also the tug forces and moment (X_T, Y_T and N_T). These correspond to Subjects S17 to S32, and S41 to S48 as indicated, who were operating in the active tug mode and consequently could use tugs at any time to complement the conventional ship controls if desired.

3.1.4 Tug Forces and Moments

As stated above, Figure 3-3 shows rudder forces and moments for the fourth run of the active groups (Groups 1 and 2, Phase 2A and Group 3 of Phase 2B). In addition, Figures 3-6A to 3-6H show these quantities for the failure run of all subjects. In this case, the rudder, rudder moment and RPM are all zero following the failure.

In the simple tug representation used in this experiment the datalog summary presents only the total nonhydrodynamic forces and moments, which comprise wind, bank and tug effects. Wind and bank forces and moments are also listed separately. Consequently, the longitudinal (X_T) and lateral (Y_T) forces and the yawing moment (N_T) can be calculated. The actual positioning of the tugs to produce these forces and moments can be deduced, or can be obtained directly from the record of tug orders prepared by the mate during that particular run.

Examination of these tug forces and moments allows one to compare pilot techniques and study their relationship to the resulting ground tracks and safety of passage.

They also allow one to establish how often and where in the channel the tugs are actually used and whether for deceleration or for control. In analyzing the tug behavior in conjunction with the ground plots the following simple configurations (i) to (x) should be considered, Figure 3-7.

These show how the direction of the lateral force and the moment on the ship are determined by the positioning of the tug or tugs. For instance, in the experiment the wind is blowing on the port beam in the final leg, exerting a counterclockwise moment on the ship and a lateral drift force to starboard. To counteract these using the available tugs when the ship lies to the right of the desired track would require a tug (or tugs) pushing on the starboard stern. A tug pushing on the port bow would counteract the moment, but would augment the drift force. If the ship lies to the left of the desired track, a port bow tug would be required. Similar conditions would exist in the turn, depending on whether the ship is outside or inside the desired transition arc. These are basically static considerations. The subsequent motion of the ship, however, will depend on the dynamic conditions at the time of application of the selected tug strategy.

3.1.5 Mean Track Line

The mean deviation off-track for all ships of a particular group was calculated at 400 foot increments along the total transit distance. The 5100 foot radius transition arc was selected as the reference track in the 45° turn. In Figure 3-8, the horizontal axis consists of the leg 1 (from points 1 to 2), the straightened arc length (from 2 to 3) and finally leg 3. At every 400 foot point the mean distance off-track for all tracks of the particular group of subjects at that section was determined, along with the standard deviation and the maximum and minimum values of off-track distance. This

representation is very instructional since all the vital information on ship position over the whole transit is readily visible. Although the $\pm$ 400 ft. width is shown constant on these figures, it must be remembered that over section 2 to 3, the turn, the distance between channel boundaries increases and then decreases again as shown in Figure 3-9. Hence an extreme data point in this leg 2 lying outside the 400 foot horizontal line does not necessarily mean a grounding has taken place. Such is not the case, however, in the other two legs.

Figure 3-8A shows the average track, the standard deviations and extremes obtained in this way for Group 1 subjects (Phase 1A - inactive, Phase 2A - active) on the 80,000 DWT tanker. The information is broken down into the cases of 2 or 4 available tugs with a total tug horsepower of 4000, and also the overall results. Similarly, Figures 3-8B and 3-8C show information for the other active and inactive ship and tug horsepower groups.

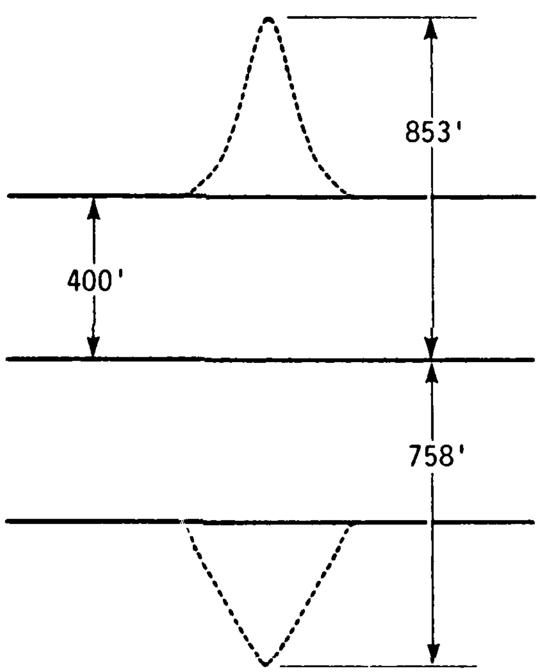


Figure 3-9. Channel Width Variations in the 45° Turn

In general, the mean track and standard deviations tend to be very similar under all combinations. The mean track line lies not too far from the $\pm$ 100 foot bias that was adopted for the performance measure calculations. The mean track in the turn for the 80,000 DWT tanker lies initially on the inside (to the right) of the transition arc, then crosses over to the outside about half way around the curve and finally ends up on the left in leg 3. The mean track for the 250,000 DWT tanker is similar. It generally lies to the inside in leg 1, until at halfway around the curve it crosses over to the left and back again in leg 3 to end up close to the centerline.

The tracks for the 250,000 DWT tanker when it has 8000 tug horsepower available in the active or inactive mode are essentially similar to the previous two; but for some reason the group with the four inactive tugs tended to stay wide to the left of the assigned track (to windward) and never crossed the reference baseline.

3.1.6 Observations on Failure Runs

The occurrence of a complete failure of rudder and engine presented great difficulty to the majority of the pilots in this scenario, particularly with the larger ship and the lower level of tug horsepower. Even many of the pilots who successfully completed the exercise without grounding had difficulties in various sections of the transit. These observations can be made directly by carefully examining the ship tracks during these failure runs (Figures 3-5A to 3-5F).

With the 80,000 DWT tanker and a total of 4000 tug horsepower available in the form of two or four tugs there was a total of eight groundings out of sixteen runs (five when the tugs were in the inactive mode using harbor pilots, and three when in the active mode using docking masters). This result could perhaps be related to the actual background of the pilots comprising each category, i.e., the harbor pilot and the docking master.

With the same horsepower tugs but a larger ship, the 250,000 DWT tanker, there were six groundings out of eight runs with tugs in the active mode, of which all four runs using two tugs resulted in groundings. With the tugs in the inactive mode there were seven groundings out of a possible eight, but in this case it was the runs with four tugs that ended up in groundings. There were thirteen groundings out of a total of sixteen runs! Therefore it appeared that 4000 horsepower was insufficient to prevent grounding of a 250,000 DWT tanker following a complete failure.

When the tug horsepower was doubled to 8000 HP there was a considerable improvement, but many groundings still occurred. With tugs active four groundings occurred in the eight runs; in the inactive mode there were only two groundings out of the eight runs, both occurring when four tugs were used. Thus there were now six groundings out of 16 runs with the doubled horsepower compared to 13 out of 16 with the original 4000 HP. It is also interesting to note that in this case the overall performance of the harbor pilots (inactive mode) was superior to that of the docking masters (active mode) which is the reverse of the conclusion drawn from the studies on the 80,000 DWT tanker with 4000 tug horsepower.

A careful examination of the plots of ship tracks during failure runs (Run 5), Figures 3-5A to 3-5F, and the corresponding time variation of tug force (X_T and Y_T) and tug moment (N_T) depicted in Figures 3-6A to 3-6H allows one to develop a qualitative description of the ship's motion after failure and the pilot's strategies in using tugs to prevent subsequent grounding. Failure occurs in line with buoy 8, marking the end of channel leg 1. The ship's trajectory immediately after failure depends upon whether the pilot has already initiated the turn or not. In the former case the ship will continue to turn until corrected by the use of tugs, (Subjects 9, 10, 15, 21 for example). But in the latter case, without engine and rudder power (rudder set amidships), the ship will continue in a straight line, (Subjects 13, 16, 19, 26, 41 and 48, for example).

There are large variations in the time lapse after failure before the pilot actually applies his tugs, (for example, Subject 9 waited about 6-1/2 minutes, Subject 10 about 3-1/2 minutes, whereas Subject 29 applied his tugs almost instantaneously, resulting in a successful transit). Then there is a further time delay before the tugs have effectively performed their function (as for example, refer to the discussion in Appendix B). The magnitude of these time delays are extremely important when related to the ship speed, as they represent the distance travelled before tug corrections are effective. The maneuvering distances available in the turn area, leg 2, and then in leg 3 are small, so any time delays are a liability.

The pilots maneuvered the larger 250,000 DWT tanker at considerably higher speeds through the turn than they did the 80,000 DWT tanker. In

this way they minimized the effect of wind (which resisted turning to the right) and following current. The speed differences between ships show up significantly in the statistical analyses (Appendix D and Section 3.2.1), but are immediately evident on examining the time variation of tug forces and moments (Figures 3-6A to 3-6H). In these plots along the horizontal time axis the times corresponding to the beginning of leg 2 (and also the point of failure) and the beginning of leg 3 (the end of the turn) are indicated by the arrow and the corresponding numeral. In the plots corresponding to the 250,000 DWT tanker data these points generally represent time intervals of about 9 to 10 minutes, but in the case of the 80,000 DWT tanker this time interval is of the order of 20 minutes or more.

As a consequence of this higher speed the tendency to drift and luff into the wind in the runs involving the larger ship is small (for example, S16, where pilot did not apply any tug assistance), but severe with the smaller ship (for example, S6).

The pilots of the 80,000 DWT tanker with its slower speed experienced difficulties in control in wind during the turn, before their tugs became effective. Once the (4000 HP) tugs were assisting effectively, they quickly restored the heading of the ship and moved it towards the track (for example, S4, S6, S18, S19). Difficulties of this nature were not experienced by the pilots on the larger ship. Once the 80,000 DWT tanker completed the turn, it was still very susceptible to current and wind drift to starboard and counterclockwise wind moments (tending to swing the bow of the ship into the wind) and moments due to the current depending on the actual ship's heading. As a result, a large number of the groundings or near groundings experienced by the smaller tanker occurred in leg 3, where considerable difficulties were encountered at the low ship speeds (for example, S2, S7, S20). The success of the ship's transit of leg 3 depended on the closeness of the ship to the centerline at the entrance to leg 3, and also the angle at which it was crossing the centerline.

Both are indicators of the amount of tug correction to be applied later to prevent grounding (for example S3, S18 and S19). The success also depends on how the tugs are deployed to counteract the wind moment and at the same time produce lateral forces on the ship to force it towards the centerline and away from the right boundary of the channel. The techniques involved generally were consistent with the procedures discussed in Section 3.1.4. In a few cases they were incorrectly applied, resulting in grounding.

The 250,000 DWT tanker, due to its greater speed and momentum, in general did not respond sufficiently quickly to the tug forces that were applied and failed to turn adequately and grounded (S13, S16, S26, S41, S48). In other cases the ship grounded after being unable to line up with the entrance to leg 3 (S14, S15, S25, S32).

In other cases grounding took place within the third leg where, during the deceleration phase, wind and current became more critical.

When the tug horsepower was doubled, it can be seen that in cases where the 250,000 DWT tanker was about to ground before entering leg 3, the tugs were able to bring the ship back into the channel but only after grounding occurred (S37, S38, S44, S45). Twice the ship failed to negotiate the turn

altogether and merely sailed essentially straight ahead despite the tug assistance (S41, S48). It appears that the speed was excessive and tugs were not applied as effectively as possible to assist the ship to turn, either an incorrect technique initially or insufficient tug power being used.

In summary, it has been qualitatively established that the success of maneuvers using tugs following a complete engine and rudder failure depends upon:

- o The initial conditions of the ship at the time of failure (heading, rate of turn, distance off track, etc.).
- o The speed of the ship at that time.
- o The time lag before tugs are used by the pilot.
- o The tug horsepower available relative to the size of ship.
- o The method of tug deployment to obtain maximum effect, as related to the dynamics of the ship (its linear and angular momentum).
- o The intensity of wind and current effects and a knowledge of their influence on ship motion.

The simultaneous analysis of the ship track and tug forces carried out above has clearly demonstrated the importance of these factors, information that can be carried over into real life operations.

3.2 STATISTICAL ANALYSES

The previous discussions in Section 3.1 were based purely on qualitative observations and correlations of simultaneous plots of ships' tracks and the corresponding controls (rudder, engine speed and tugs) that were used. The following sections of this report will consider the quantitative implications derived from statistical analyses of the performance measures discussed in Section 2-12. These statistical analyses were based on Analysis of Variance procedures (Anova 1 and Anova 2) on the experimental data involving the two main comparisons:

1) Ship type (80,000 DWT and 250,000 DWT tankers) and

2) Available Tug horsepower (4000 and 8000 BHP).

Tables 2-7 and 2-8 present the two Anova Source Tables showing the significant dependencies of the performance measures on the various factors (main effects) and their interactions to significance levels of 0.001, 0.01, and 0.05. Table 2-7 (Anova 1) clearly indicates significant variations in most performance measures with the five factors (main effects) as well as their interactions. Table 2-8 (Anova 2) on the other hand, shows very few main effects when tug horsepower was varied; tug moment contribution was the principal measure depending significantly on the horsepower factor.

In both tables however, the variations in performance measures depend significantly on channel leg.

In order to understand quantitatively the importance of the various factors more fully it is necessary to examine in detail the higher order significant interactions. This was done and the results are presented in Appendix D. This discussion will attempt to summarize the main conclusions that can be drawn from these comparative analyses. Not all the performance

measures treated in the analyses will be discussed in detail.

3.2.1 Mean Speed

Table D-1 (main effect, A) indicates that the mean speed of the 250,000 DWT tanker was significantly greater than that of the smaller ship. Table D-49 (interaction AD) shows that whereas the speed of the smaller ship increased significantly between the first and second replicate runs (Runs 2 and 3), but not thereafter, the speed of the larger ship remained constant throughout. The difference between the two ships in each run was still significantly different, with the 250,000 DWT tanker always travelling faster. The interaction AE, Table D-46, further indicates that the larger ship was always faster in the first leg and in the turn, but in the final leg its speed and that of the 80,000 DWT tanker were comparable, due to the deceleration process. The presence of tugs in either the active or inactive mode (interaction ACD, Table D-48) did not influence the speed of the larger ship in replicate runs, but with the 80,000 DWT ship in the first replicate run (Run 2) the mean speed was higher when tugs were active than when they were inactive. The speed variation with leg number (interaction ED, Table D-47) was significant in all cases, as it should be, since the exercise required slowing down from leg 1 to leg 3. With replication, the tendency was to increase speed in the turn and in the final leg; this is obviously a reflection of the fact that the 80,000 DWT tanker increased speed during the first two replicates whereas the 250,000 DWT ship tended to maintain constant speed thoughout.

The interaction CHB, Table D-78, in the Anova 2 Analysis indicated that the mean speed can be significantly different depending on the available tug horsepower, the tug mode and the number of tugs used. When two tugs with a total horsepower of 8000 were employed in this active mode the mean speed was lower than when the two tugs were inactive; the tugs were being used effectively in reducing speed and controlling the ship. However, when four tugs were used the opposite was true; the mean speed was lower when the tugs were inactive than when they were active. Apparently the pilots felt more secure in travelling at higher speed in the active mode, knowing that they had tug assistance immediately available in case of any emergency occasioned by mishandling the ship besides equipment failure.

However, when only 4000 HP was available there were no significant differences in mean speed for the two tug modes for either two or four tugs.

It therefore appears that two tugs were used more effectively than when four were available. Table D-80 (interaction CHBED) shows that significant differences in mean speed occur only in the turn (leg 2). Although there was a tendency to increase speed with repetitive runs, this only occurred when two tugs were used at either horsepower.

The recognition and understanding of this variation in speed between the two ships have an important influence in the interpretation of the variation of many of the other measures that were examined in this study.

3.2.2 Swept Path

The fact that the analysis indicated a significant difference (67 feet) between the mean swept paths of the two ships is an obvious conclusion. Even under ideal conditions of perfect

alignment the swept paths (in this case, the beam widths) of the ships would differ by 45 feet. As an afterthought, therefore, it may have been preferable to use a normalized performance measure, swept path/beam or length, in making more realistic statistical comparisons. As can be readily observed from the ship tracks (Figures 3-4A to 3-4X) and as indicated by these statistical analyses there is a continuous increase in swept path from the first leg to the final leg, the swept path being greater for the larger ship.

For the 250,000 DWT ship, the analyses indicated that the swept path was greater when tugs were used in the active mode than when they were inactive, Table D-45 (interaction AEC). The interaction CBE, Table D-73, indicates that, for the 250,000 DWT tanker the swept path is significantly larger in the final leg when four tugs were present but inactive. However with either two or four tugs but in the active mode, there was no difference in swept path in any leg. The tug number and the tug mode appear to be important only in the final deceleration phase. When two active tugs were employed the swept path in leg 3 was larger (+22 feet), and smaller (-29 feet) when four active tugs were used than the corresponding conditions with inactive tugs. A significant reduction in the swept path resulted in the third leg with repetitive runs; although only amounting to twenty feet it was statistically significant.

3.2.3 Distance Off-Track Contribution

This contribution to the performance index Ji represents $(Y_{RMS}/100)^2$ where Y_{RMS} is the conventional RMS deviation off-track measure. Hence Y_{RMS} can be found from

$$100\sqrt{\text{Distance Off-track Contribution}}$$

The main effects results showed that the overall deviation off-track contribution (or the equivalent RMS deviation off-track) was independent of ship size and tug mode but significantly dependent on the tug number. No significant variation occurred with run replication. The largest value occurred in the turn (Y_{RMS} = 160 feet), the median value in the final leg (Y_{RMS} = 89 feet) and the smallest in leg 1 (Y_{RMS} = 42 feet).

The interaction effects, however, provide more information on the breakdown of these dependencies. The interaction AD, Table D-27, indicates that while the larger ship maintains an overall Y_{RMS} of about 110 feet throughout all the repetitive runs, for the 80,000 DWT tanker the value decreased with run order from 124 feet to 92 feet. In Table D-28 (interaction BE), the distance off-track in the turn was dependent on the tug number; larger values when four tugs were employed (179 feet) compared with two tugs (137 feet).

From the third order interaction, ABD, Table D-29, it can be seen that on Run 2 (the first of the repetitive runs), the deviation off-track was larger with the 80,000 DWT tanker (147 feet) when four tugs were used compared with two tugs (97 feet), although such differences did not exist in subsequent runs. The 250,000 DWT tanker, on the other hand, did not show any such variations either with tug number or with replicate runs. During the first run the 80,000 DWT ship had a much higher deviation off-track (147 feet) than that of the larger ship (114 feet). Using the four tug configuration, the deviation off-track improved in subsequent runs for the 80,000 DWT ship. On the other hand,

with the two tug configuration there was no variation with run number.

The interaction ADE, Table D-30, indicates that the performance of the 80,000 DWT ship in the turn improved with repetition; and principally between the first and second runs (Run 2 and Run 3). The larger ship again showed no such variation with run order. In the turn the deviation off-track (188 feet) of the smaller ship was significantly larger than that of the larger ship (153 feet) during the first run. This was only the case in the turn, and elsewhere the performances of the two were comparable.

The interaction CDE, Table D-31, shows a significant improvement in off-track performance during the first two repetitive runs when tugs were in the inactive mode, but no such variation when they were active. The major difference between the tug modes occurred in the turn, leg 2, and on the initial replicate run (Run 2).

The significance of tug number can be assessed by examining the interaction BDE, Table D-32. There was no variation in distance off-track in each leg with repetition when two tugs were employed. However, when four tugs were used there was a significant improvement in track-keeping in the turn between Run 2 and Run 3 (226 feet and 169 feet). Otherwise in the other two legs, and in the final run (Run 4) there was no significant variation. For the 250,000 DWT ship there were also significant differences in the turn, the highest deviation occurring with the four tug configuration.

The only effect derived from the Anova 2 analysis was a variation with leg number; the maximum deviation of 148 feet occurring in the turn (leg 2). Otherwise, there was no overall significant difference due to horsepower, tug number, tug mode or run number.

3.2.4 Rudder Contribution

The rudder contribution to the performance index Ji represents the square of the ratio of the RMS rudder angle to the maximum available rudder angle, that is $(\delta_{RMS}/35)^2$.

Table D-1 (main effect, A) indicates that the rudder contribution (or equivalently the RMS rudder angle used) is greater for the larger ship (23^o against 19^o) undoubtedly due to much greater influence of wind and current on the larger ship, and its greater inertia. At the same time the mean ship speed was greater for the larger ship, but the increased rudder efficiency was apparently insufficient to compensate for the environmental effects. From Table D-2 (main effect, B) it can be seen that the RMS rudder increased with tug number (19^o, 22^o) while tug mode had no influence Table D-3 (main effect C). The rudder contribution also decreased with repeated runs, from 22^o in Run 2 to 19^o in Run 4, Table D-4 (main effect D). There also appeared to be a substantial increase in rudder angle used from leg 1 to leg 3 (15.5^o, 20.3^o, 25.3^o) Table D-5 (main effect E). This is expected in view of the need for rudder use in turning and in the final deceleration phase to counteract wind and current moments when the rudder efficiency has decreased due to decreased hull speeds.

Finally, the interaction AE, Table D-35, explains how the rudder usage is distributed among the legs and ships respectively. Although more rudder was used with the larger ship in the first leg (17.8^o) and in the turn (23.7^o) than with the 80,000 DWT tanker (12.8^o and 16.2^o respectively), the amount of rudder used by both ships in the final deceleration phase was comparable (about 25^o). For the 250,000 DWT tanker the RMS rudder

angles used in the turn and in the final phase were similar (24° and 26° respectively). In the case of the 80,000 DWT ship, on the other hand, significantly more rudder was used in the final leg (24.8° against 16.2°).

3.2.5 Tug Moment Contribution

Table D-1 (main effect A) shows that the tug moment contribution to Ji was significantly larger for the 250,000 DWT tanker than for the 80,000 DWT tanker. In fact, the contribution for the 80,000 DWT ship was very small indicating very little use of tugs for control. The contribution overall was much greater when 4 tugs were used, Table D-2 (main effect B). Obviously, as indicated in Table D-3 (main effect C) the tug mode is important as tugs were not to be used in the inactive mode unless a complete mechanical failure took place. There was no significant change in overall tug contribution with replicate runs, Table D-4, (main effect, D) but as would be expected, and can be clearly seen from Section 3.1.4, the control increased from leg 1 to leg 3, Table D-5 (main effect, E). Very little use of tugs is made in the first leg, more in the turn, but most occurs in the final deceleration phase where tug assistance is most important. The interaction AB, Table D-36, indicates that the tug usage with the smaller ship was minimal whether two tugs or four tugs were available, but there was significantly more use of tugs with the larger ship. There was also a much larger tug moment contribution with four tugs than with two tugs, approximately twice, which corresponds to 40% more RMS moment being used with 4 tugs.

The tug moment contribution, as shown in Section 2.11, is represented by the square of the ratio of the RMS tug moment to the maximum moment attainable. In transferring from tug contribution to RMS moment, one must be careful to recognize that the maximum moment can be variable. The maximum moment can be represented by 9 x horsepower available x length of ship (Section 2.11), and consequently for the Phase A experiments and the corresponding Anova 1 analyses the maximum tug moments for the 80,000 and 250,000 DWT are in the ratio of their respective lengths, that is, 0.70. In the Phase B experiments and the Anova 2 analyses a fixed ship size was used (250,000 DWT tanker) but horsepower was varied (4000 HP and 8000 HP). As a result the maximum moments are in the ratio 1:2. Denoting the maximum moment for the 80,000 ship with 4000 HP by N_o (= $9 \times 4000 \times 763 = 27.468 \times 10^6$ lb ft), we can derive the following table.

Ship Type	Tug Horsepower	Max. Moment
80,000 DWT	4000	N_o
250,000 DWT	4000	$1.42\ N_o$
250,000 DWT	8000	$2.84\ N_o$

Hence the RMS tug moment,

$$N_{TUG\ RMS} =$$

$$N_{MAX}\sqrt{\text{Tug Contribution.}}$$

The information presented in this table along with this expression should be used to compare tug moments. The variation in tug contribution with leg, Table D-38 (interaction AE), clearly shows again how tugs are used minimally with the smaller ship, and then only in the final stages. The 250,000 DWT tanker, on the other hand, although not using tugs to any degree in the initial leg, uses more tug

moment in the turn, and a considerable amount in the third leg (30% of the maximum moment). Table D-39 (interaction BC) also shows quite clearly the difference in active tug usage between the two ships, and confirms that more use was made of four tugs than two as stated previously. Table D-42 (interaction ACE) further confirms the relative use of tugs for the two ships, and the strong leg dependence, particularly for the 250,000 DWT ship.

The Anova 2 analysis indicated for the 250,000 DWT ship that there was no significant variation in the tug contribution with repetitive runs Table D-57 (main effect D) as was also shown in the Anova 1 analysis. Again tug usage was significantly different in the three legs, Table D-58 (main effect E), increasing with leg number.

In relation to the effect of available tug horsepower on tug usage, Table D-54 (main effect H), shows a significant difference in the tug contribution with the value in the 4000 HP case higher than in the 8000 HP case. With 4000 HP tug power available 21% of the maximum possible moment was being used. However, in terms of RMS tug moment (since the maximum moment at 8000 HP is double that corresponding to 4000 HP) this means that practically the same amount of tug moment was used in both cases. That is, advantage was not taken of the full potential of the tugs.

Table D-64 (interaction, HE) similarly shows that the contributions from the 4000 HP tugs are significantly larger than the corresponding values with the larger tug power. In terms of RMS moments, however, the values in the turn are very close (15%, 17%) but in the final leg the RMS moment is somewhat higher with the larger horsepower (32%, 40%). The numbers in brackets here refer to the RMS moment as a percentage of the maximum moment on the 250,000 DWT ship when the tug horsepower is 4000 HP. The first number refers to the 4000 HP case, the second to the 8000 HP case.

The influence of tug number on the tug contribution can be derived from Table D-66 (interaction, HB). Again the tug contribution is greater with the smaller tug power when 4 tugs are used. Converting this measure into actual RMS moment, the moment is also about 30% larger. At 4000 HP there is a significant increase in the tug contribution and also the actual moment when the larger number of tugs is used. At the higher level of tug power there is an insignificant change with tug number, although the RMS moment actually used with the two tugs was larger (about 1.7 times) than when the four tugs were employed.

Finally with two tugs the RMS moments are greatest with the larger horsepower, but with four tugs available the reverse is true, the larger moment is applied in the 4000 HP case. The same result is indicated in Table D-68 (interaction CHB) for the active mode.

Table D-69 (interaction, CHE), shows the variation with leg number. In both cases of horsepower the tug contribution is practically zero in the first leg, larger in the turn, and largest in the final stage. The tug contributions in both the turn and the final leg are significantly different depending on tug power available, being larger for the smaller power. Again, if one considers the RMS moments that are being applied in each case it can be seen that although they are relatively close in the turn, in the final leg about 40% more moment is exerted at the

higher power level. When the interaction HEB, Table D-70, is studied it is found that only in leg 3 are significant differences found depending on tug number for both horsepowers. At 4000 HP the contribution (and the RMS moment) is larger when 4 tugs are available but at 8000 HP the contribution and moment are larger when 2 tugs are used. This result supports findings discussed previously in this Chapter.

3.2.6 Inherent Risk Factor, α_2

In summarizing the statistical information in Appendix D pertaining to inherent risk (α) and the combined performance measure (J), attention will be directed towards α_2 and J_2. By consulting the material in Appendix D, the reader can in the same manner form conclusions on the behavior of the other factors α_1, α_2, J_1, and J_3. The inherent risk factor α_2 is significantly greater for the larger ship. This is mainly a result of the higher mean speed of this ship as discussed previously. There is no significant effect of tug number (Table D-2, main effect B) or tug mode (Table D-3, main effect, C). Table D-4 (main effect, D) indicates an increasing risk between Run 2 and the final run (Run 4). There are significant differences in the risk factor in the different legs, (Table D-5, main effect, E) with the highest value in the turn (74%), the next highest in the first leg (43%) and a small value in the final leg (7%). These values are to be expected due to the nature of the waterway.

The risk factor is strongly dependent on ship size as shown in Table D-19 (interaction AD). With the smaller ship the risk increased with repetitive runs, particularly the first two (Run 2 and Run 3). This can be correlated with the increase in mean speed on this ship after Run 2 as discussed previously. The larger ship, however, does not show any significant variation in risk (about 50%) with successive runs. This also correlates with the previous findings that the 250,000 DWT tanker maintains constant mean speed throughout the successive runs. For each run the risk was significantly greater with the larger ship. This difference also shows up clearly when the risks in each leg are compared (Table D-20, interaction AE). The risk is much higher in the first leg (59%) and also in the turn (85%) with the larger ship. In the final leg, however, where the mean speeds of the two ships are comparable the difference in risks is insignificant. This conclusion also is consistent with the earlier finding on the mean speed distribution for the two ships.

A significant variation in α_2 occurs in the turn (leg 2) depending on the number of tugs available, Table D-21 (interaction BE). Its value is higher when two tugs are used. In the other legs the variation in α_2 due to tug number is insignificant. However, for both the 2 tug and 4 tug configurations there is a significant difference in risk by leg number. In all cases, the risk is greatest in the turn and lowest in the final leg. Table D-22, (interaction ED) illustrates how the risk changes during repetitive runs for each channel leg. It demonstrates that in the turn, the risk increases significantly between Run 2 and Run 3. In leg 1 there is a significant difference between the first run and the final run, whereas there is no variation in leg 3. Again, this is consistent with the mean speed observations. Table D-23 (interaction, ADE) shows how this information can be broken down to demonstrate the contributions of the two ships. In the case of the larger ship the risk is high in both leg

1 and the turn, consistent with the ship's higher mean speed throughout. The 80,000 DWT tanker on the other hand shows increasing risk in the turn and leg 1 but not in leg 3. By Run 4 the difference in risk between the two ships is not significant in the turn nor in the final leg. The difference is still significant in the first leg, where the speed of the 250,000 DWT tanker is higher than that of the smaller ship.

Table D-60 (interaction DBH), obtained from the Anova 2 analyses indicates that the only time there is a difference in risk, α_2, due to horsepower is when 4 tugs are used and occurs in Run 2. The risk is higher when the lower horsepower is used.

3.2.7 Combined Performance Measure J_2

This measure considers the combined effect of the contributions from rudder, tug, deviation off-track and inherent risk as described in Section 2-11. Table D-1 (main effect A) indicates that J_2 is significantly larger for the 250,000 DWT ship and this can be attributed to its much larger rudder contribution and greater inherent risk. J_2 is also larger when 4 tugs are used, Table D-2 (main effect, B), and this is mainly due to the larger distance off-track contribution. Tug mode has no significant effect, Table D-3 (main effect, C), nor does run repetition, Table D-4 (main effect, D). However, there is a strong influence of channel leg, Table D-5 (main effect, E) with distance off-track making a substantial input in the turn. J_2 in the final leg is greater than in the first leg; this is caused by the increased rudder and tug contributions despite the fact that the inherent risk had decreased in leg 3 over leg 1. The use of four tugs yielded a higher J value in the turn, but made an insignificant effect in the other two legs, Table D-8 (interaction, BE). For both tug configurations the values in leg 3 were always higher than in the first leg but much lower than in the turn. The effect of tug mode, apparent from Table D-9 (interaction, CDE), is to give a significant difference in J_2 values in the turn, but nowhere else. In the first run (Run 2) in leg 2 the J_2 is much higher when the tugs were inactive than when they were active. However, after that first run the differences due to tug mode were non-existent. In the Anova 2 analyses there were no significant main effects due to the five factors except for leg dependence and no significant interactions.

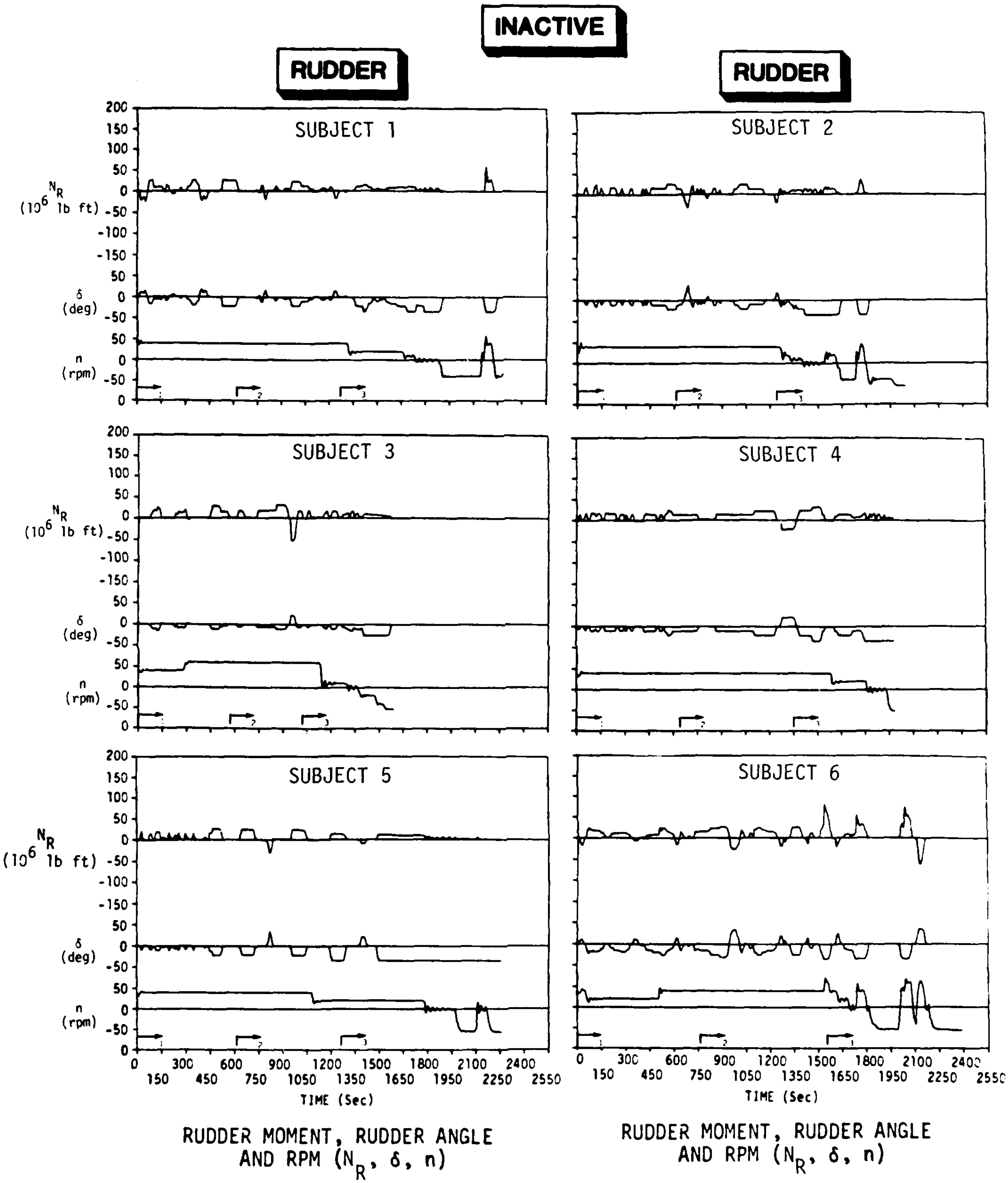


Figure 3-2A. Time Variation in Rudder Moment, Rudder Angle and RPM - Inactive Tug Mode - Final Replicate Run (R4) Subjects S1 to S6

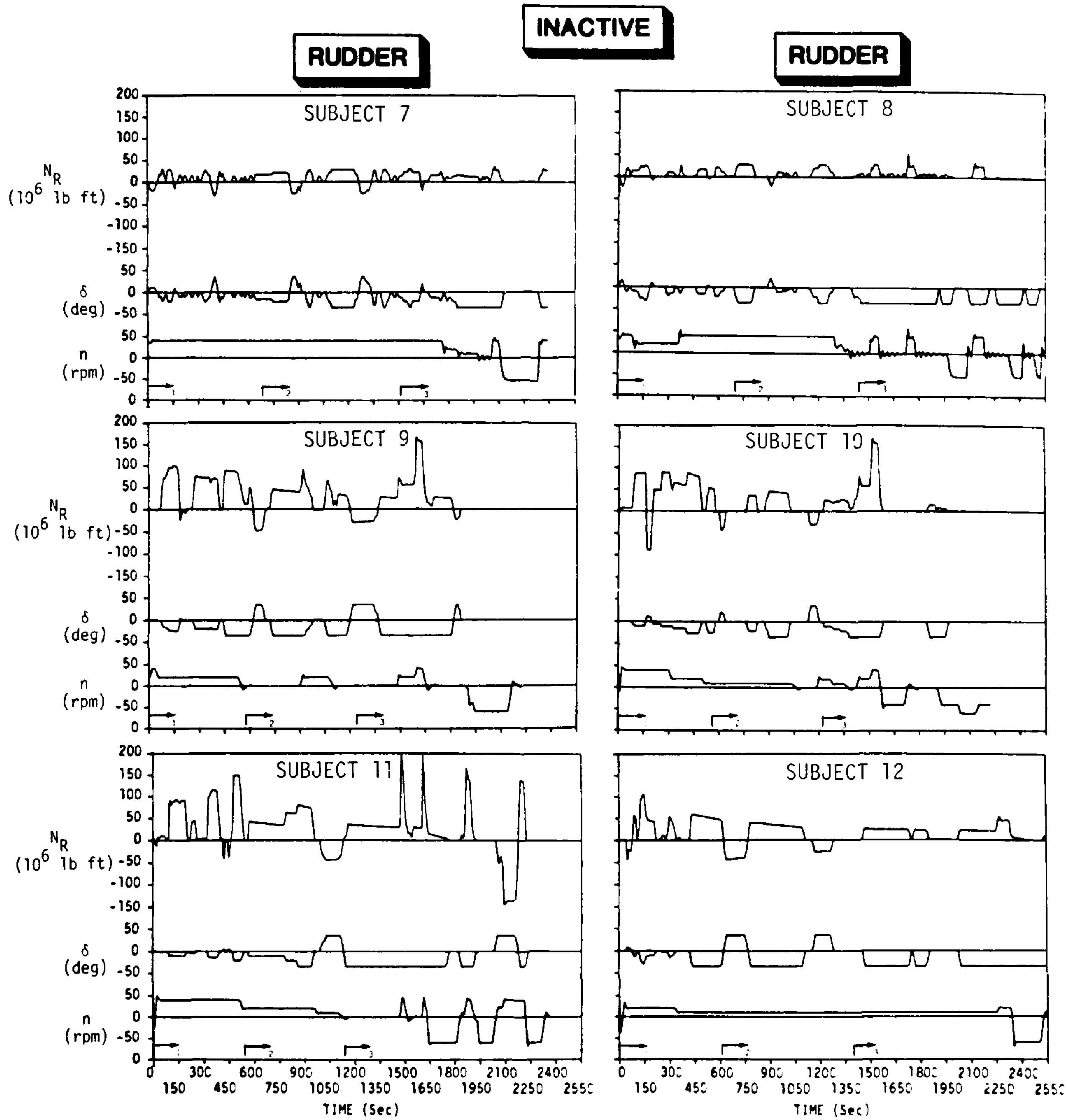


Figure 3-2B. Time Variation in Rudder Moment, Rudder Angle and RPM - Inactive Tug Mode - Final Replicate Run (R4) Subjects S7 to S12

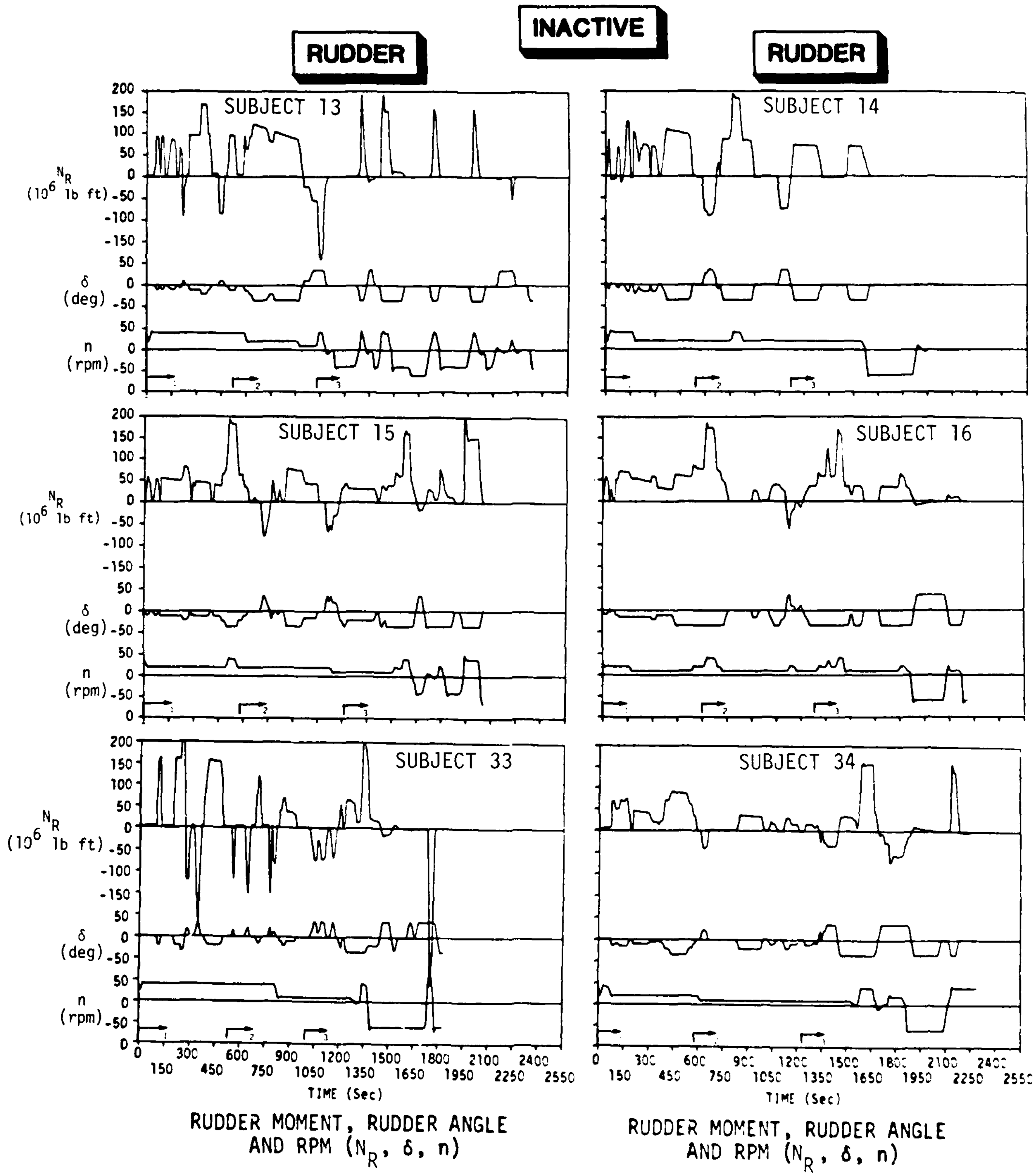


Figure 3-2C. Time Variation in Rudder Moment, Rudder Angle and RPM - Inactive Tug Mode - Final Replicate Run (R4) Subjects S13 to S16, S33 and S34

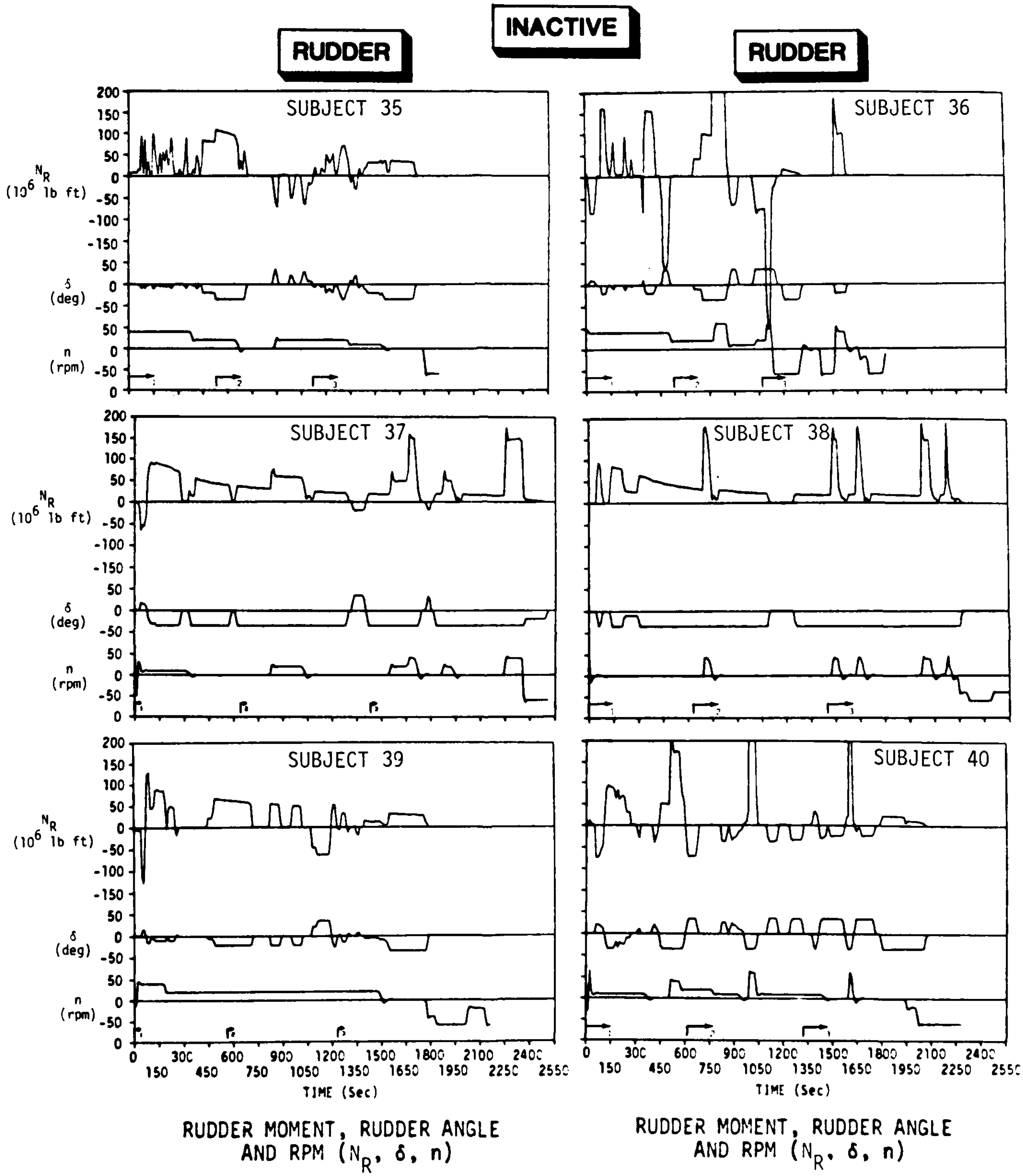


Figure 3-2D. Time Variation in Rudder Moment, Rudder Angle and RPM - Inactive Tug Mode - Final Replicate Run (R4) Subjects S35 to S40

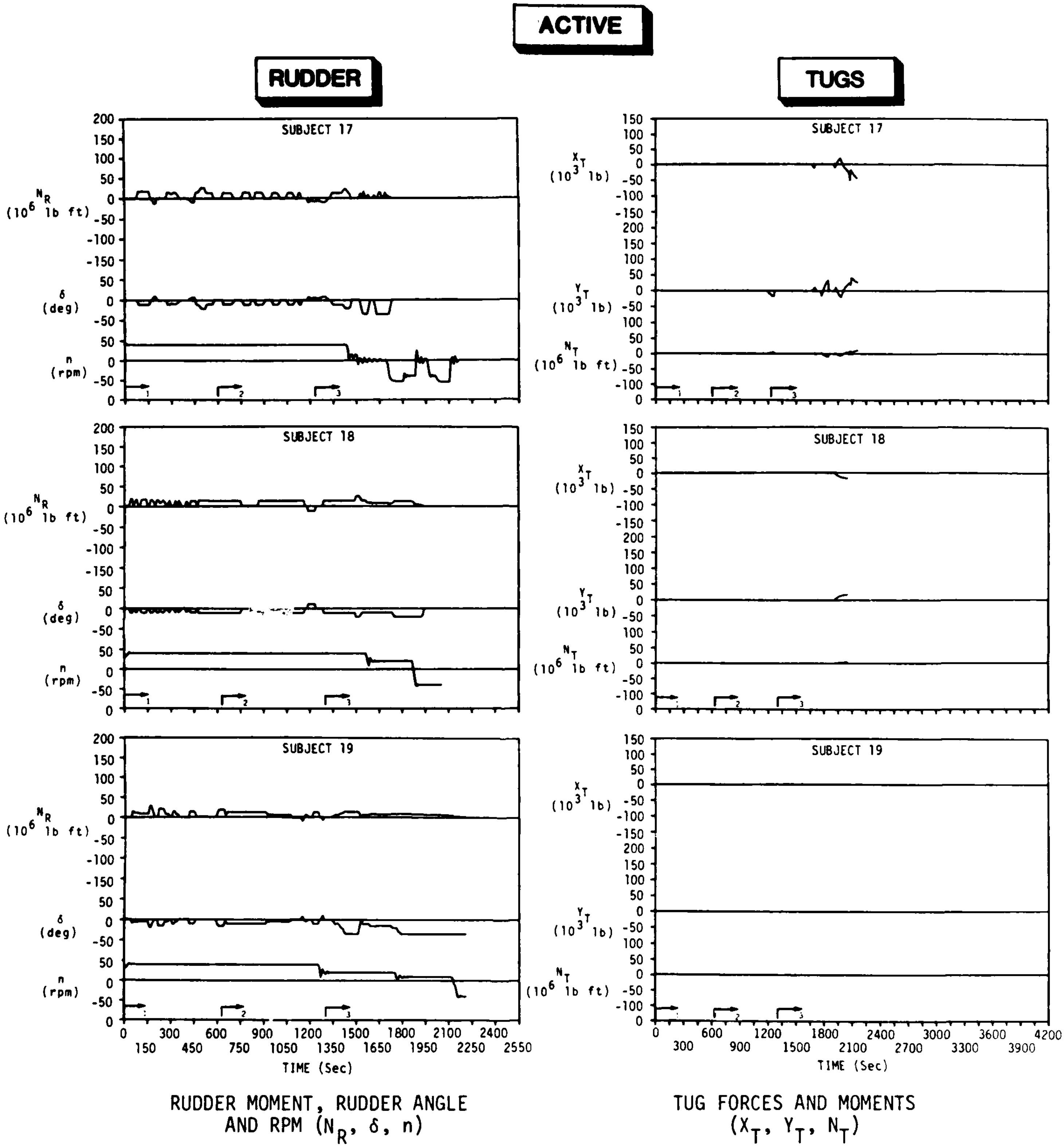


Figure 3-3A. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S17 to S19

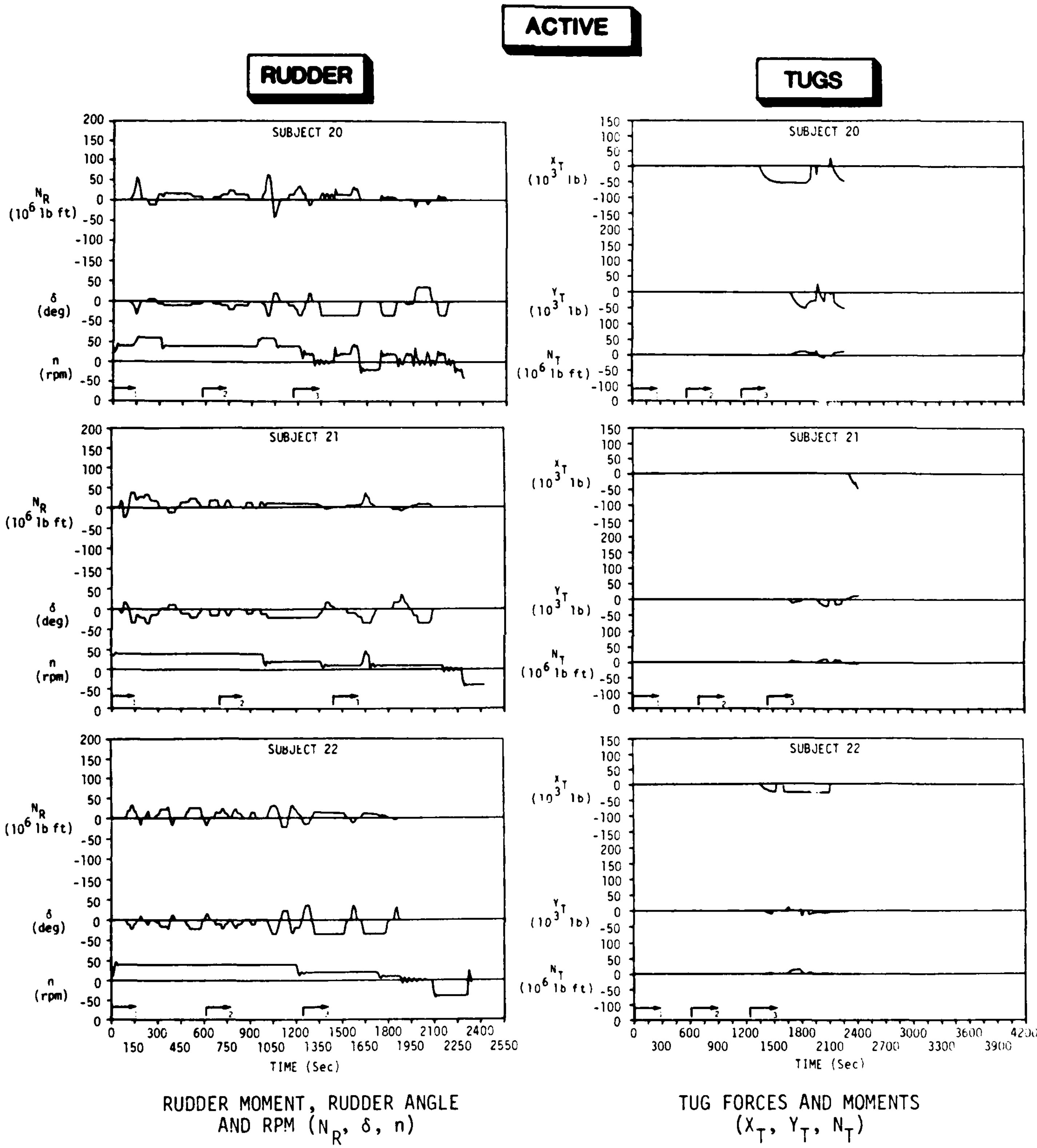


Figure 3-3B. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S20 to S22

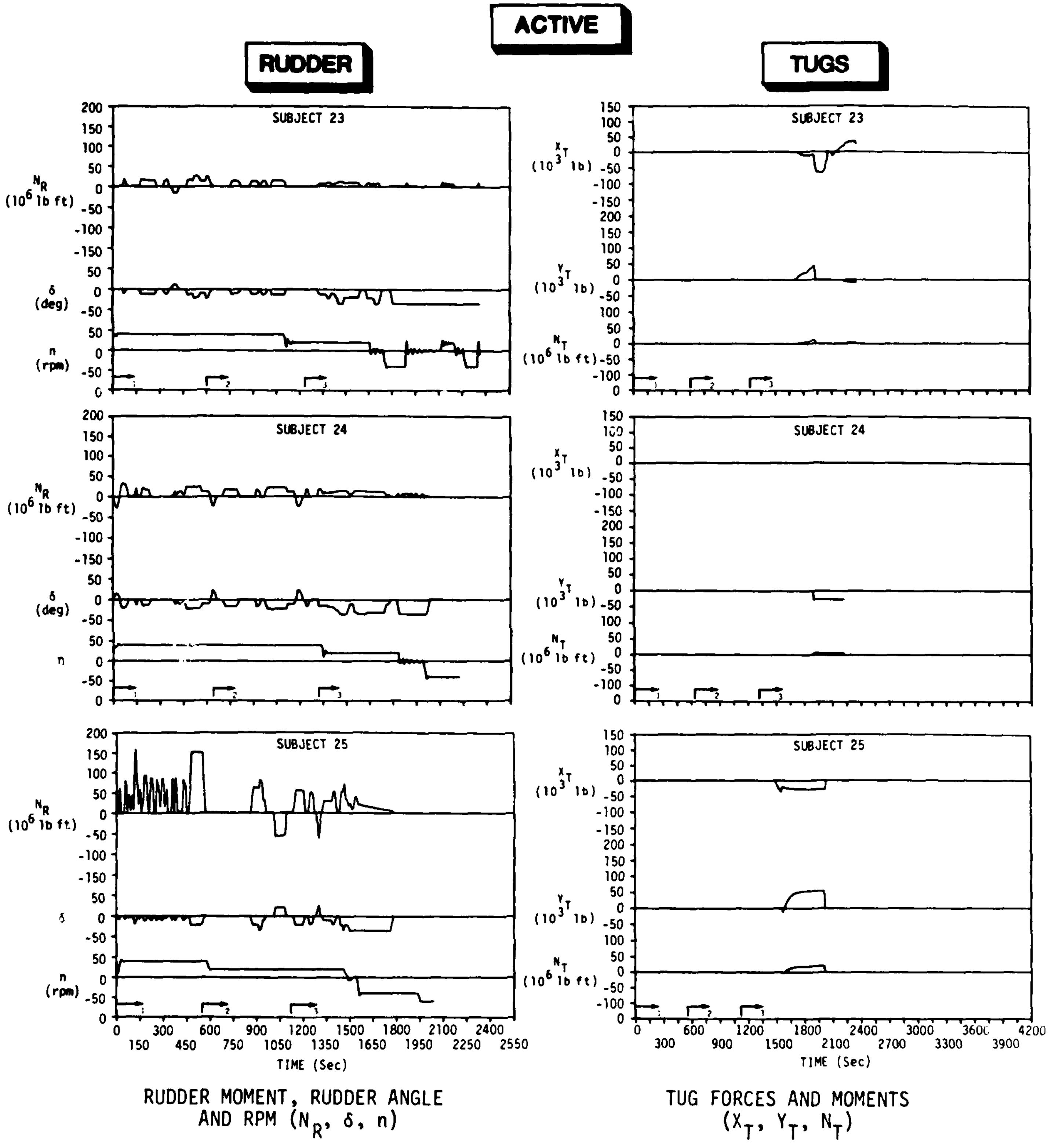
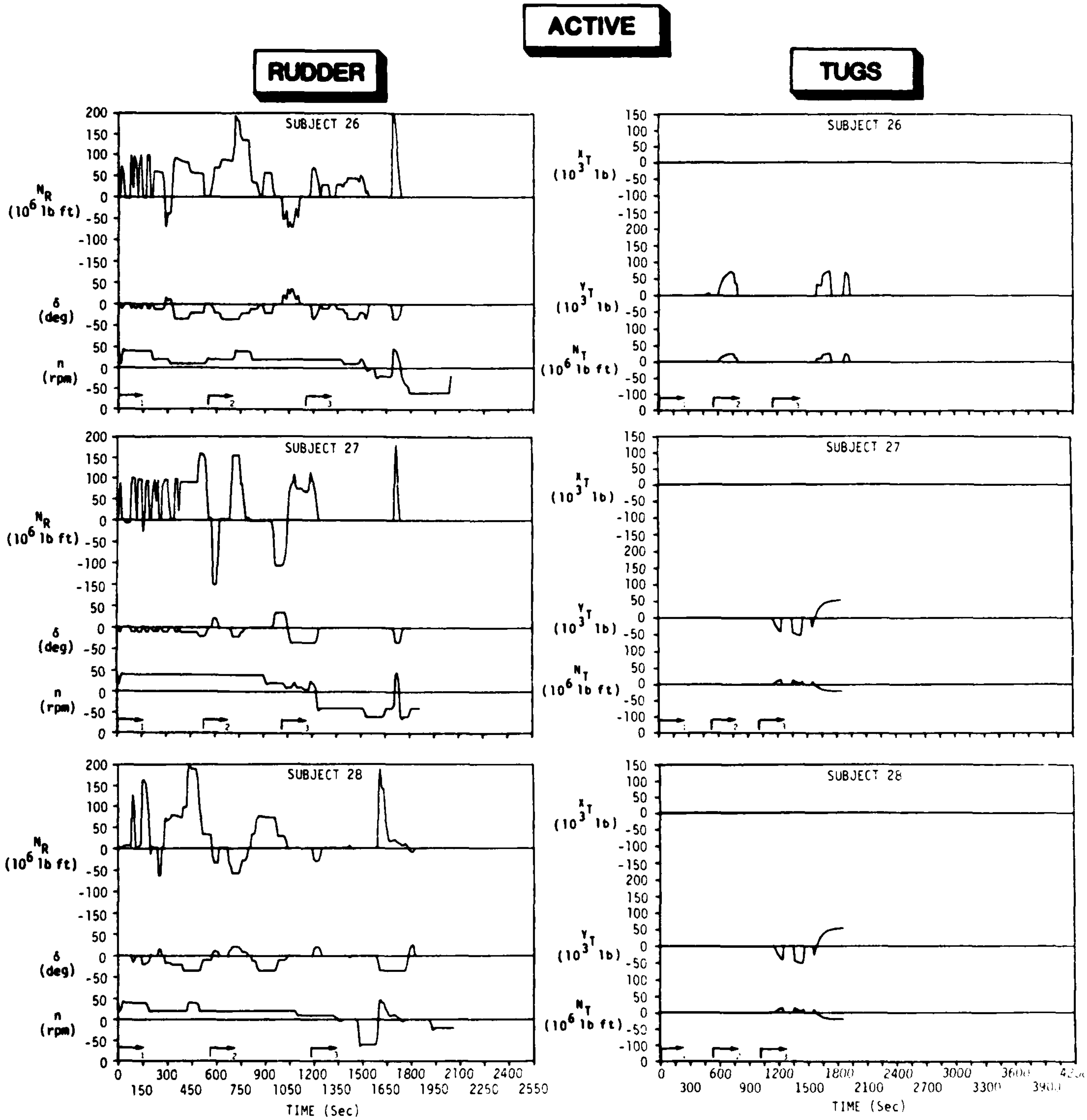


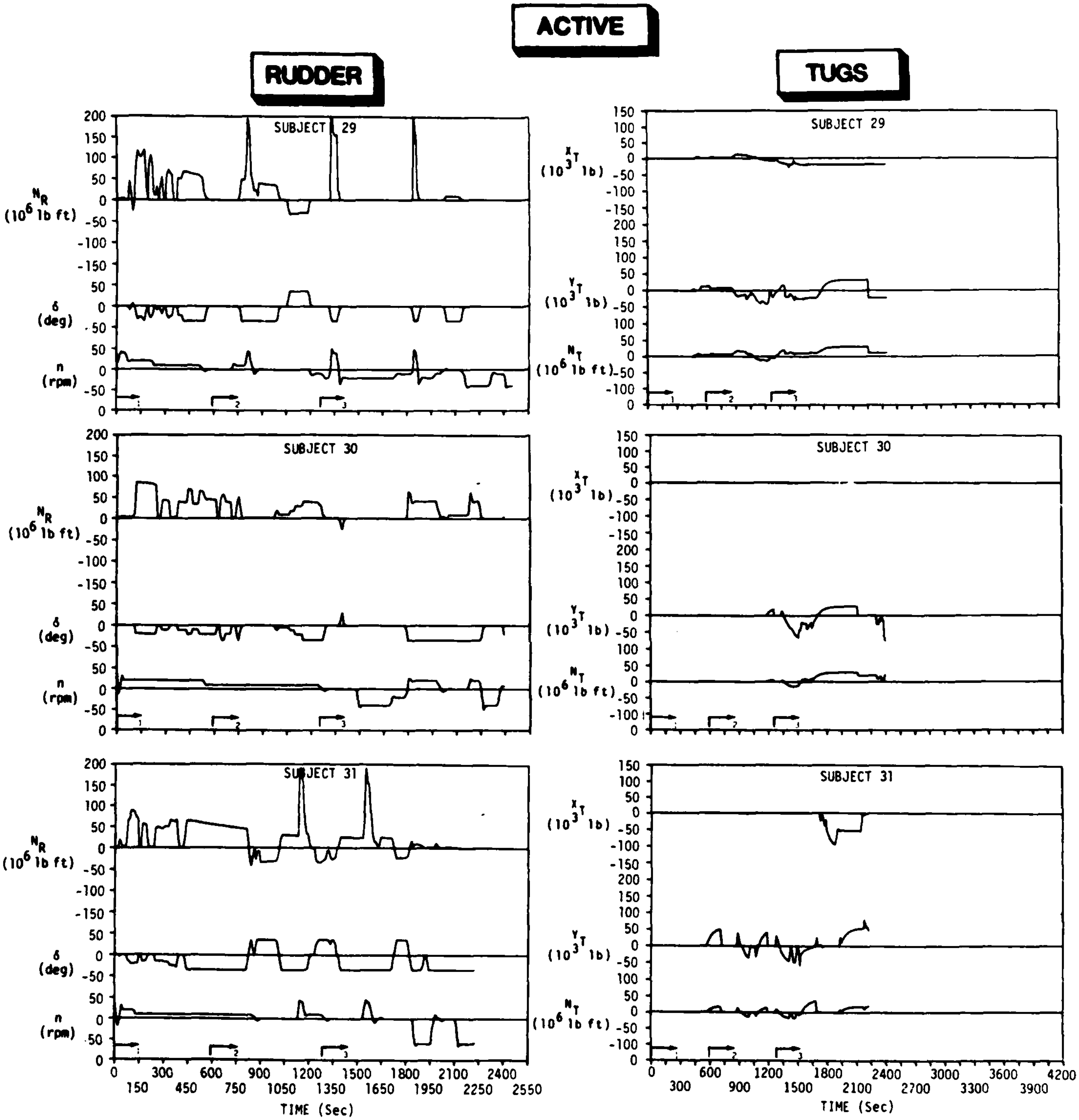
Figure 3-3C. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S23 to S25



RUDDER MOMENT, RUDDER ANGLE AND RPM (N_R, δ, n)

TUG FORCES AND MOMENTS (X_T, Y_T, N_T)

Figure 3-3D. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S26 to S28



RUDDER MOMENT, RUDDER ANGLE AND RPM (N_R, δ, n)

TUG FORCES AND MOMENTS (X_T, Y_T, N_T)

Figure 3-3E. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S29 to S31

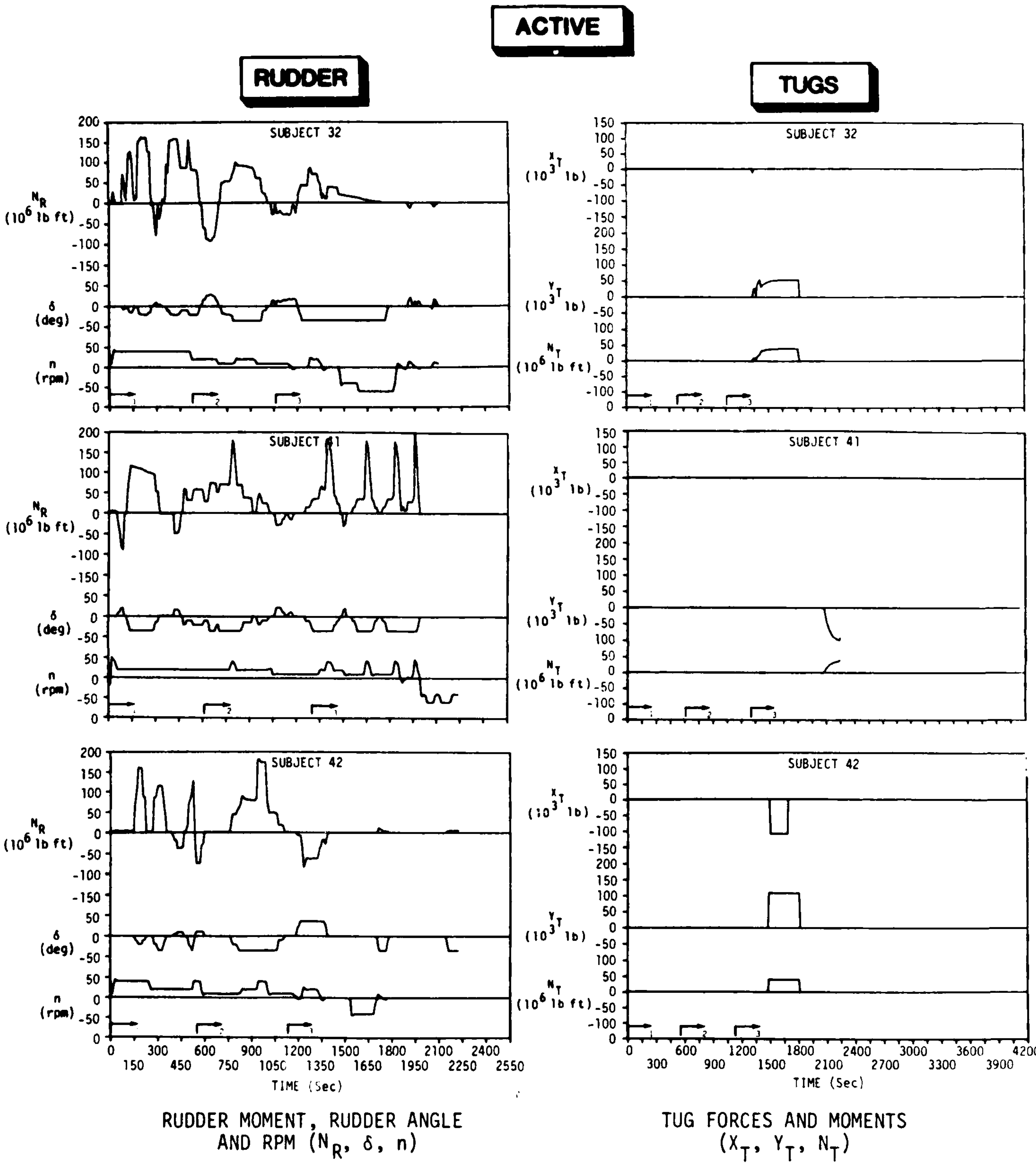
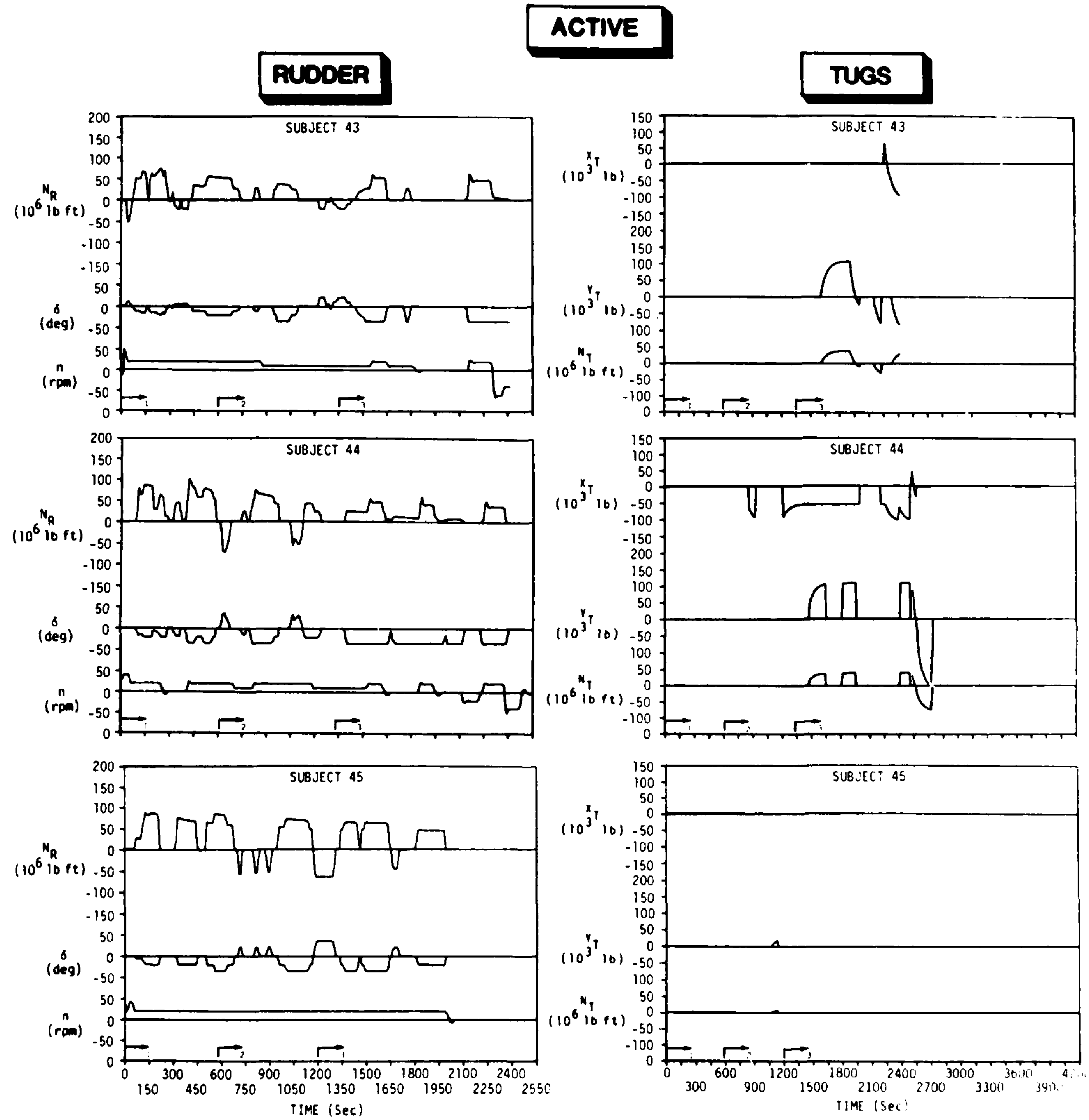


Figure 3-3F. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S32, S41, S42



RUDDER MOMENT, RUDDER ANGLE AND RPM (N_R, δ, n)

TUG FORCES AND MOMENTS (X_T, Y_T, N_T)

Figure 3-3G. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S43 to S45

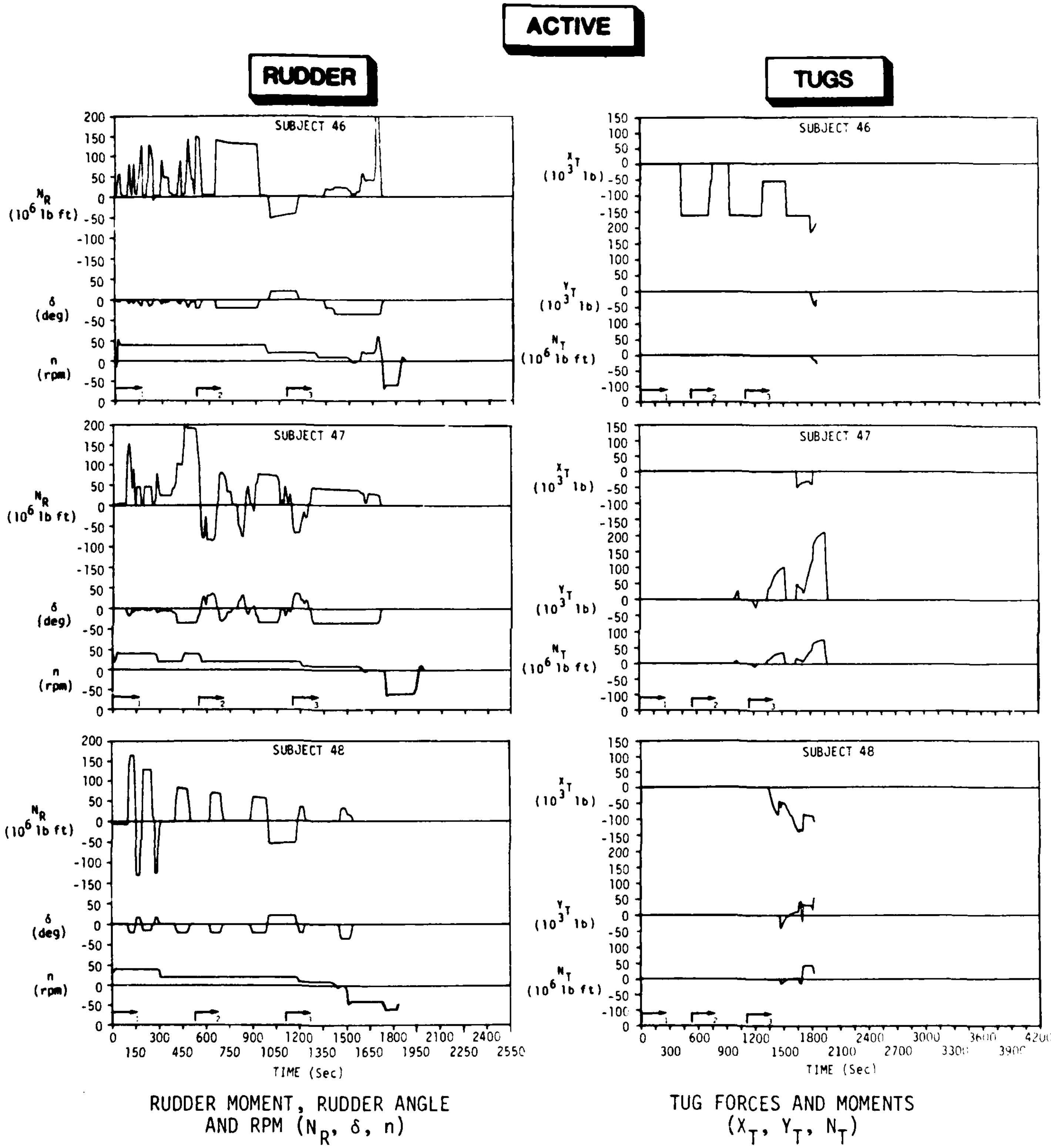


Figure 3-3H. Time Variation in Rudder Moment, Rudder Angle and RPM - Active Tug Mode - Tug Forces and Moments Subjects S46 to S48

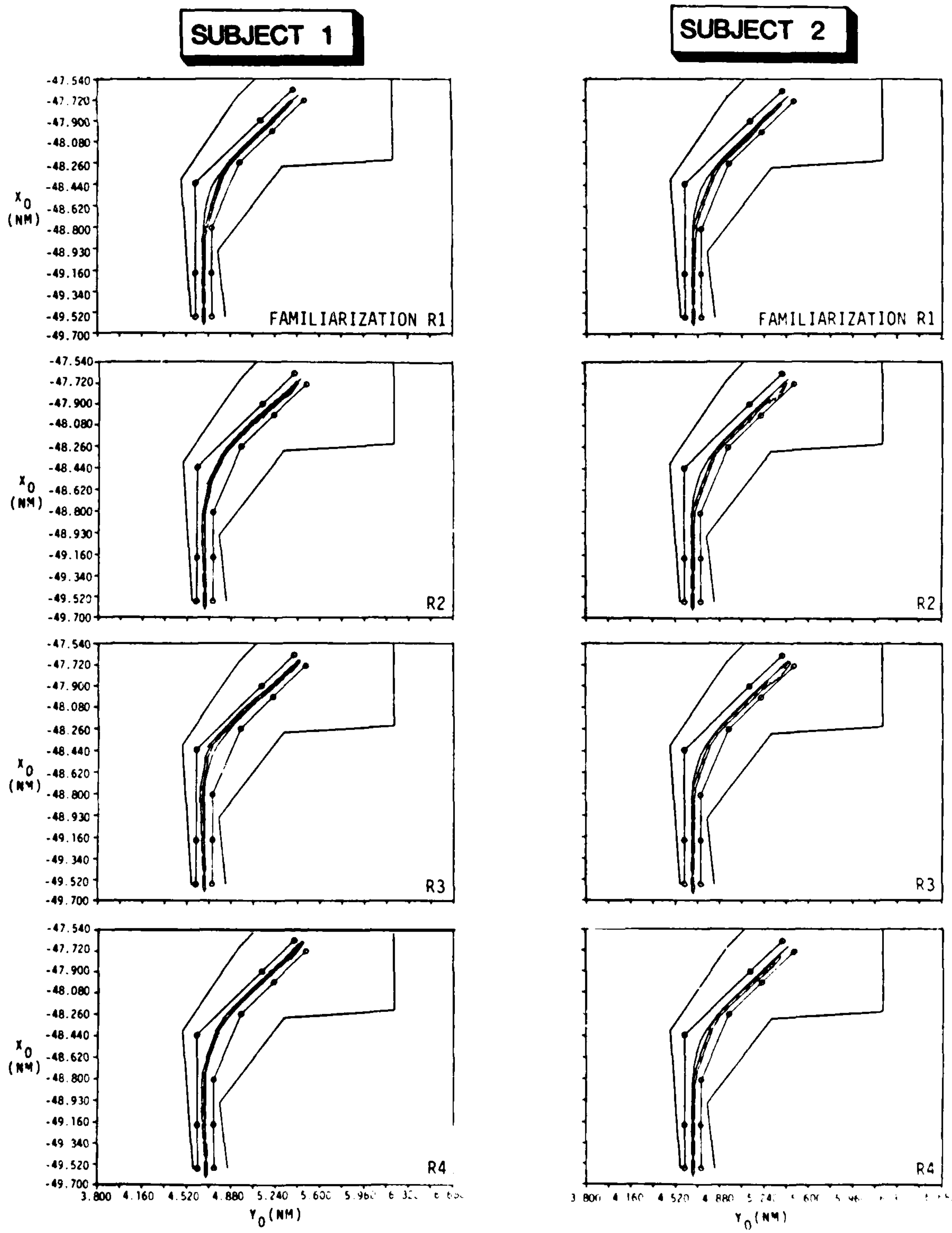


Figure 3-4A. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S1 and S2

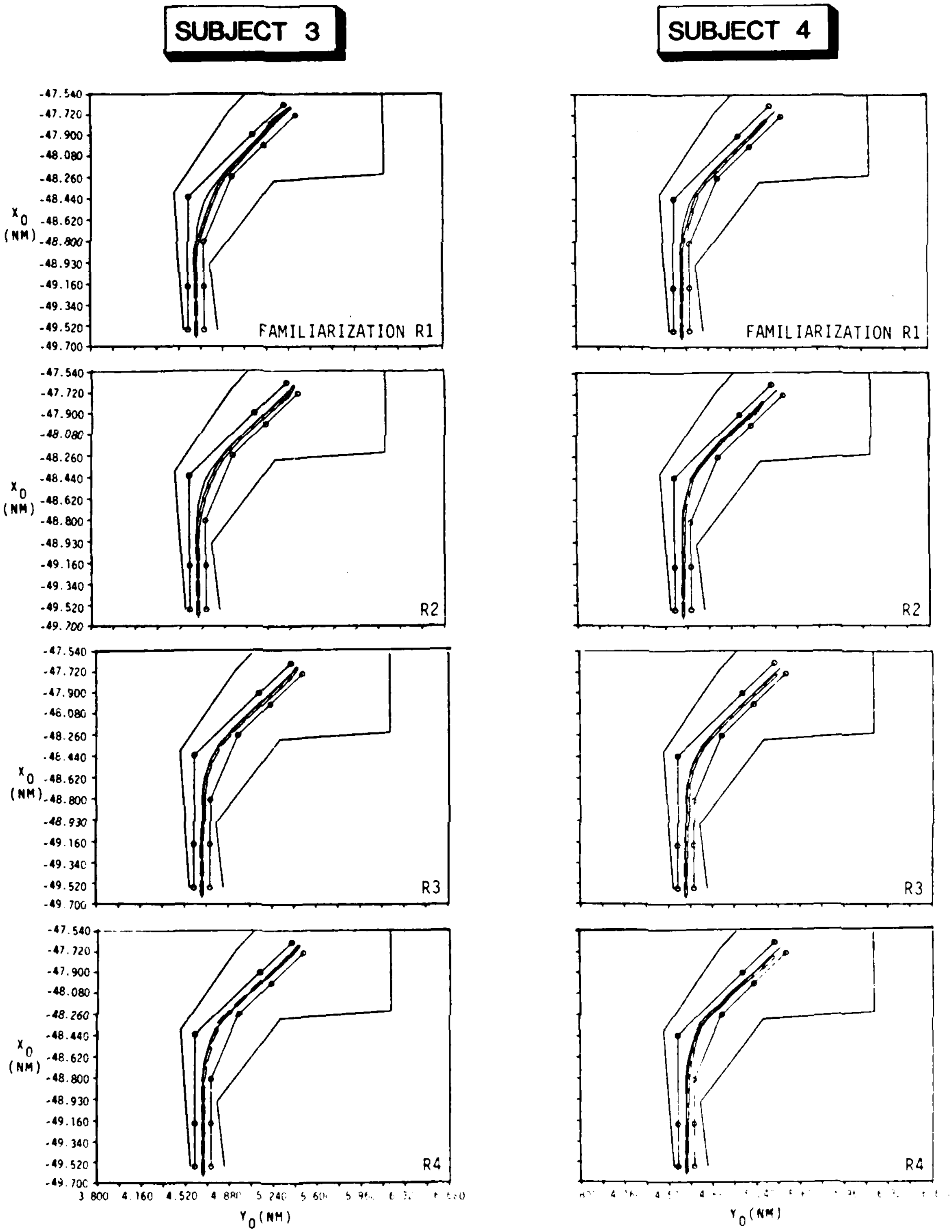


Figure 3-4B. *Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S3 and S4*

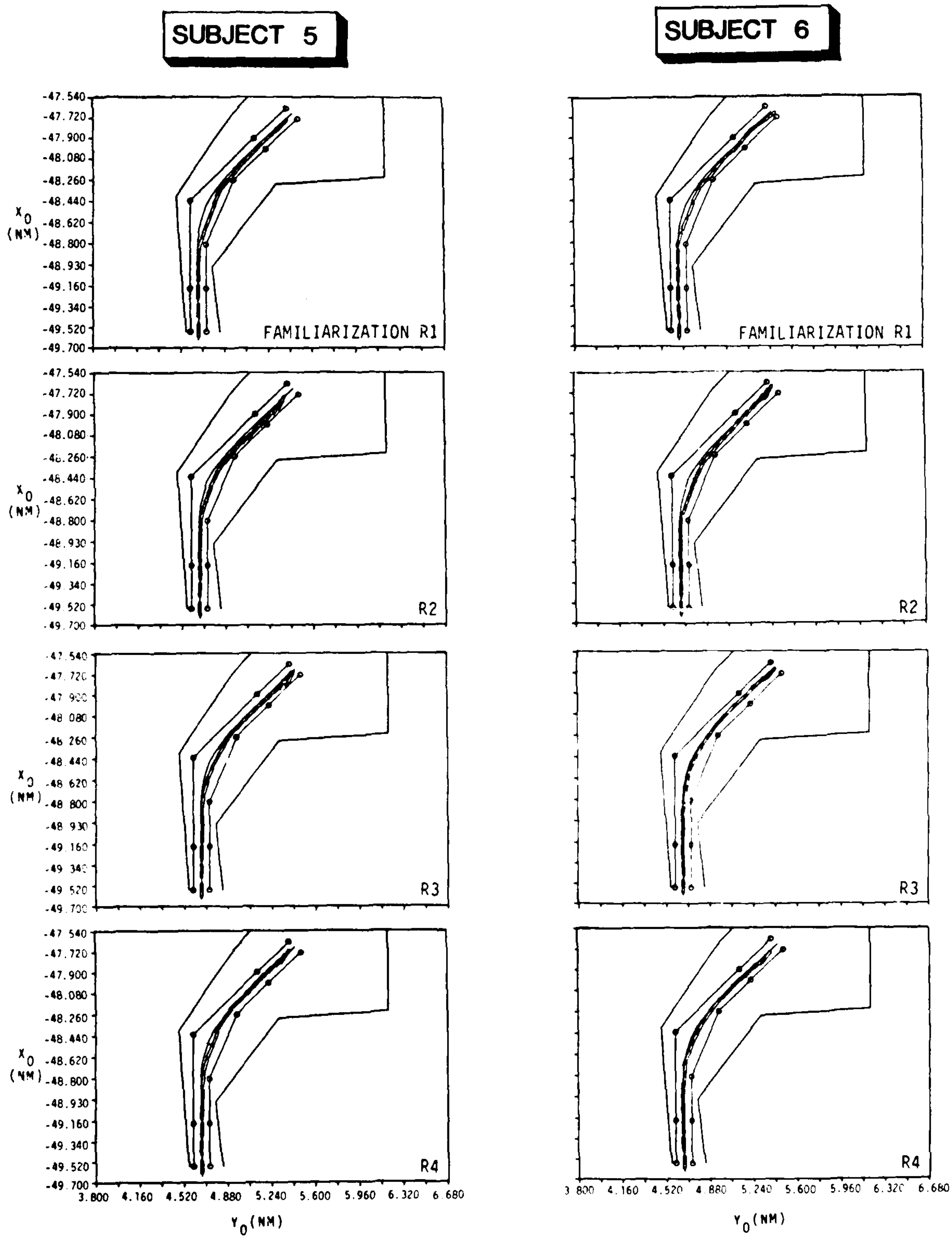


Figure 3-4C. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S5 and S6

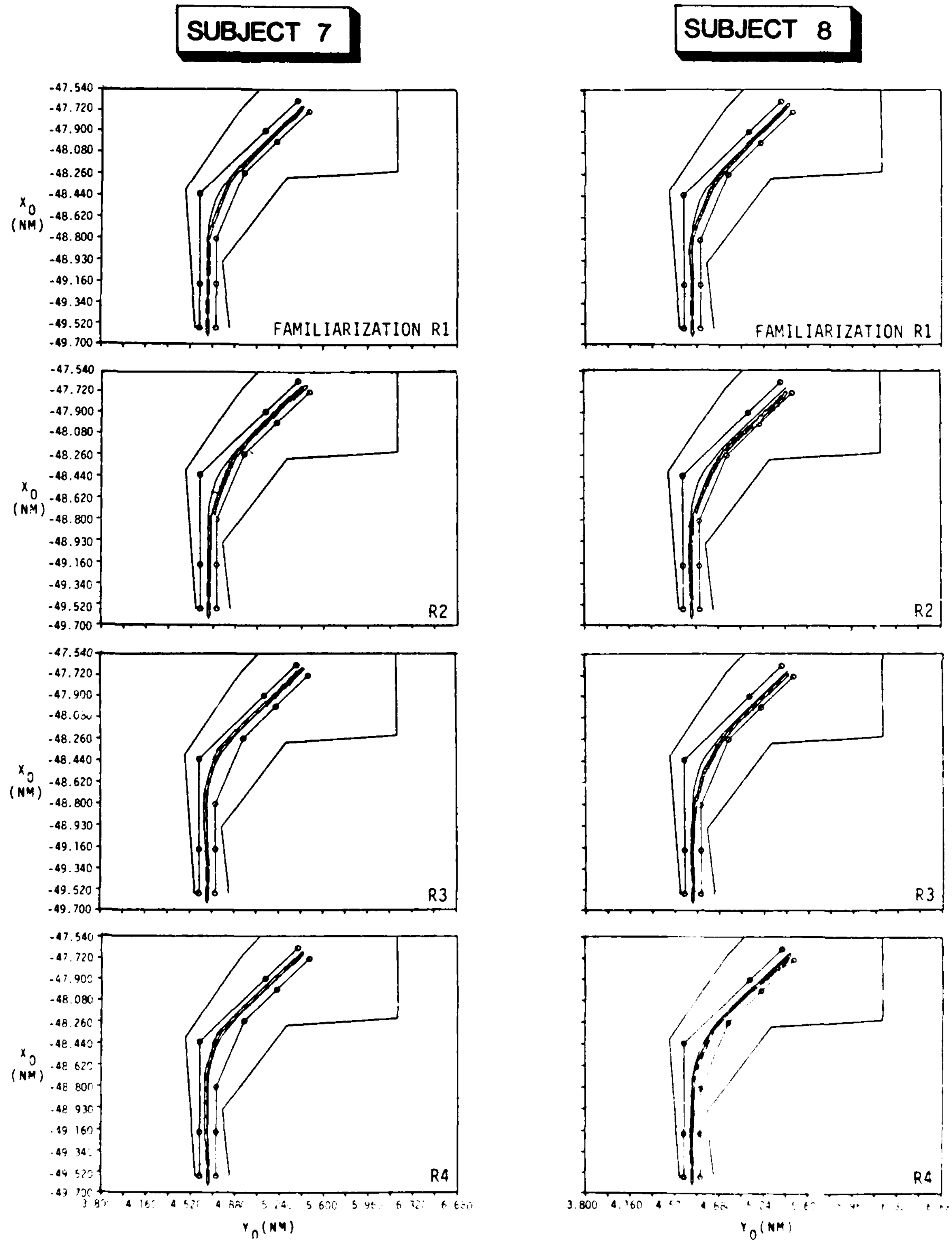


Figure 3-4D. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S7 and S8

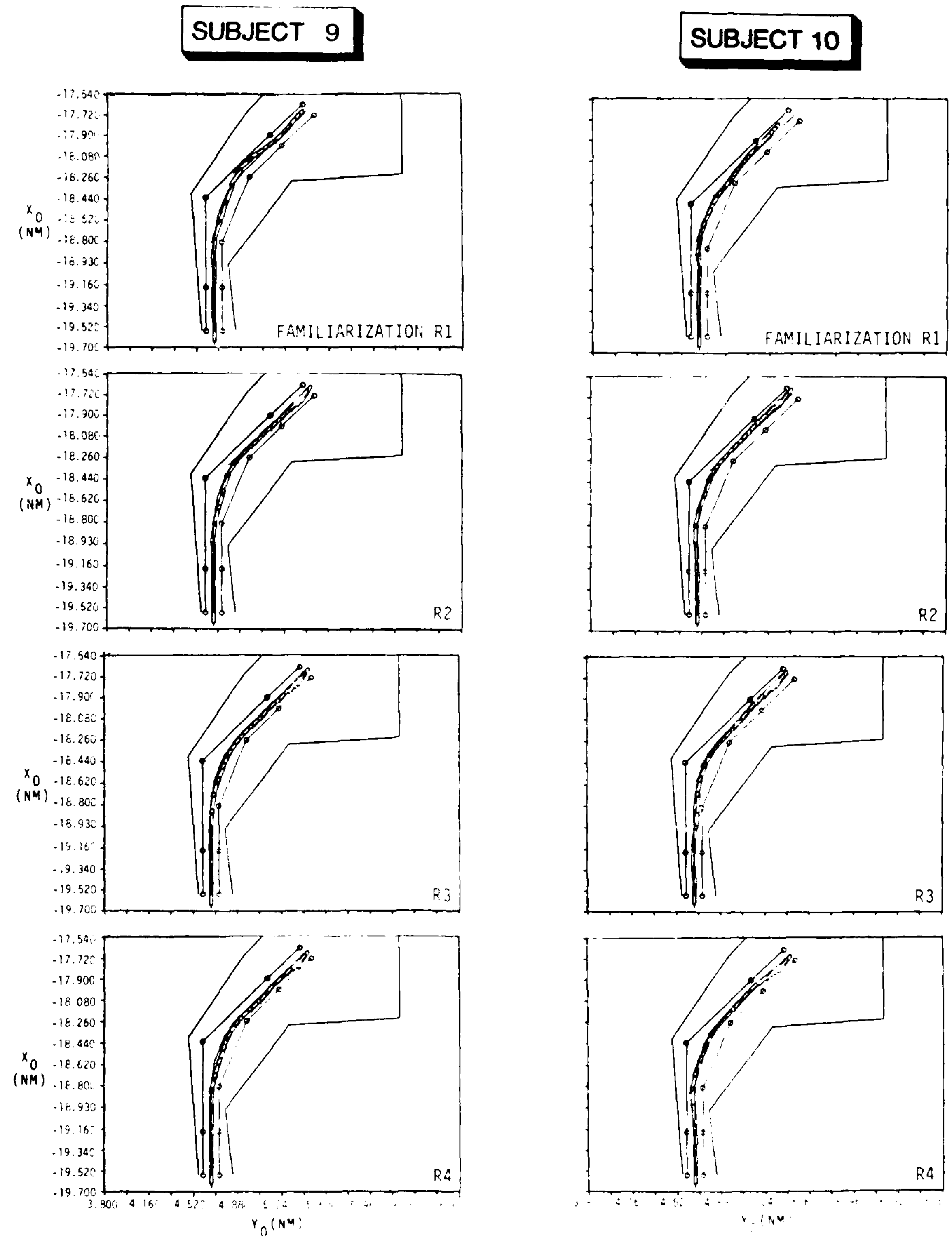


Figure 3-4E. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S9 and S10

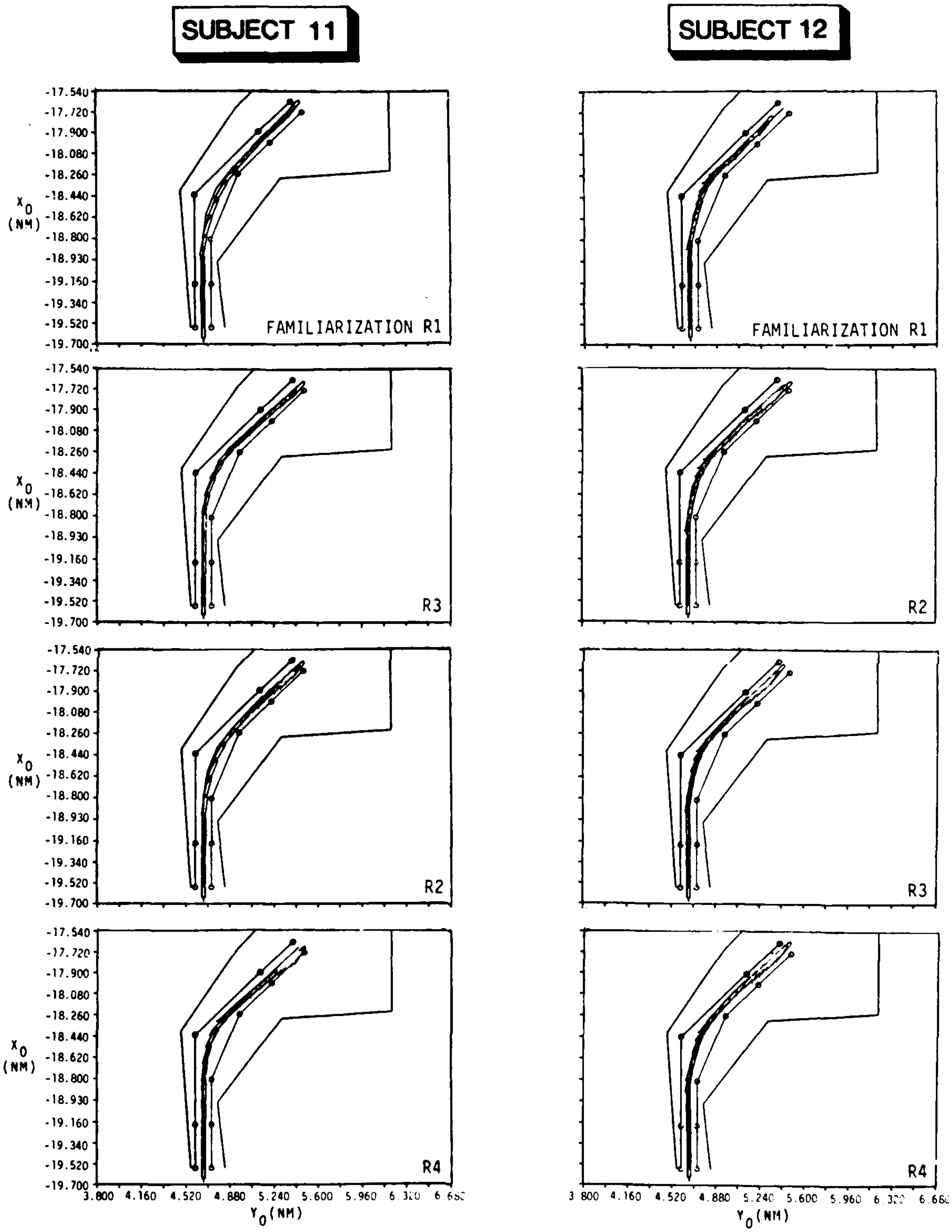


Figure 3-4F. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S11 and S12

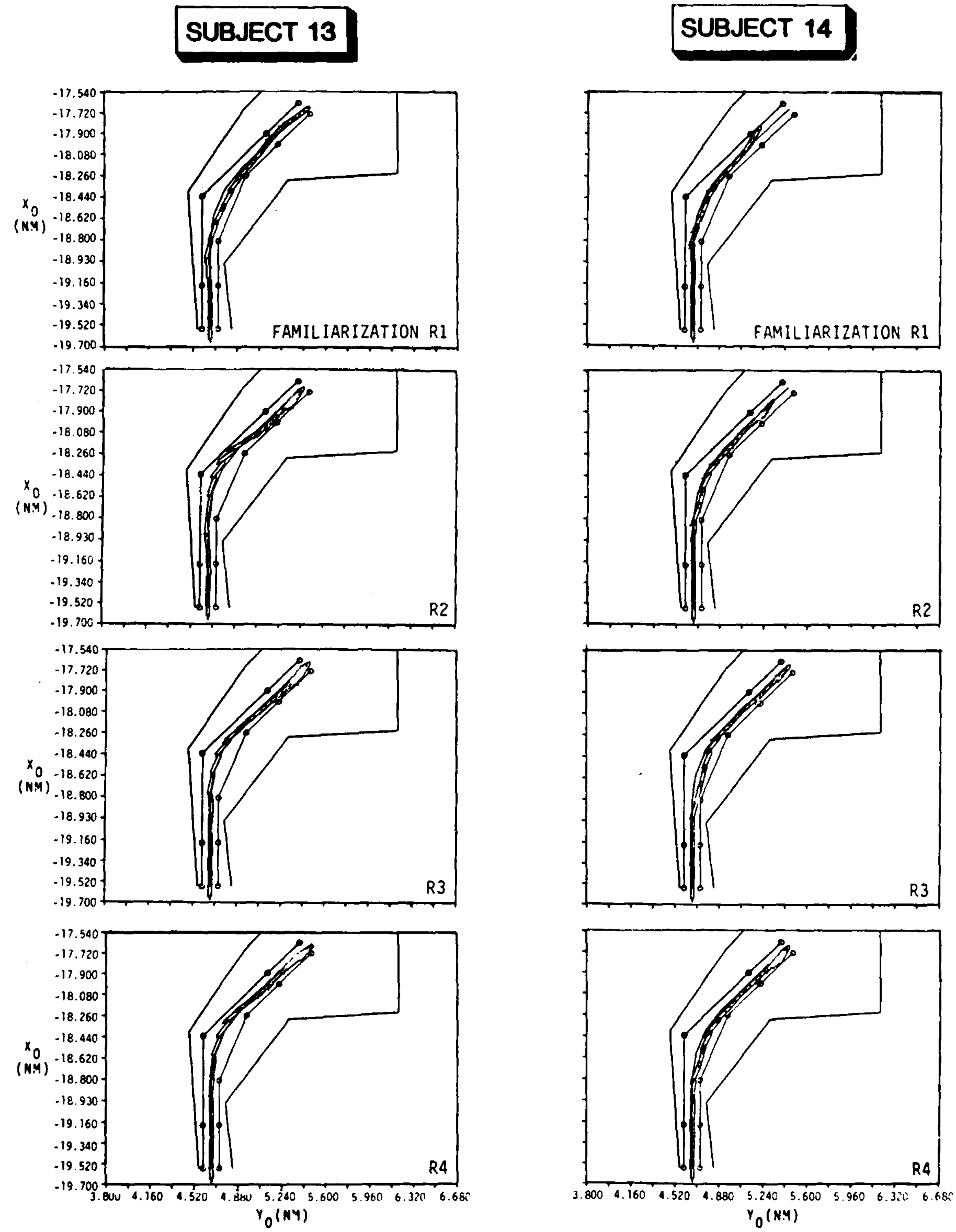


Figure 3-4G. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S13 and S14

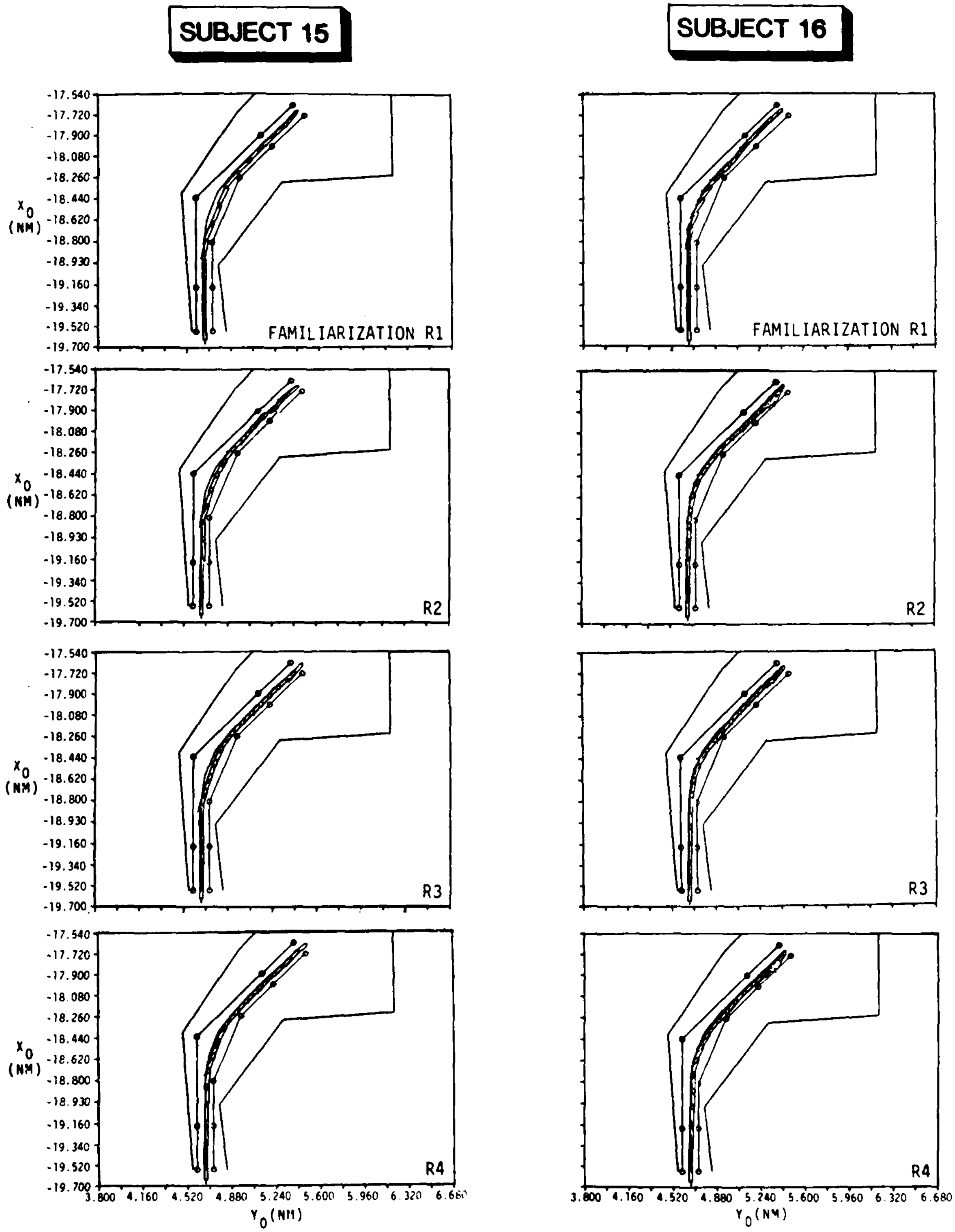


Figure 3-4H. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S15 and S16

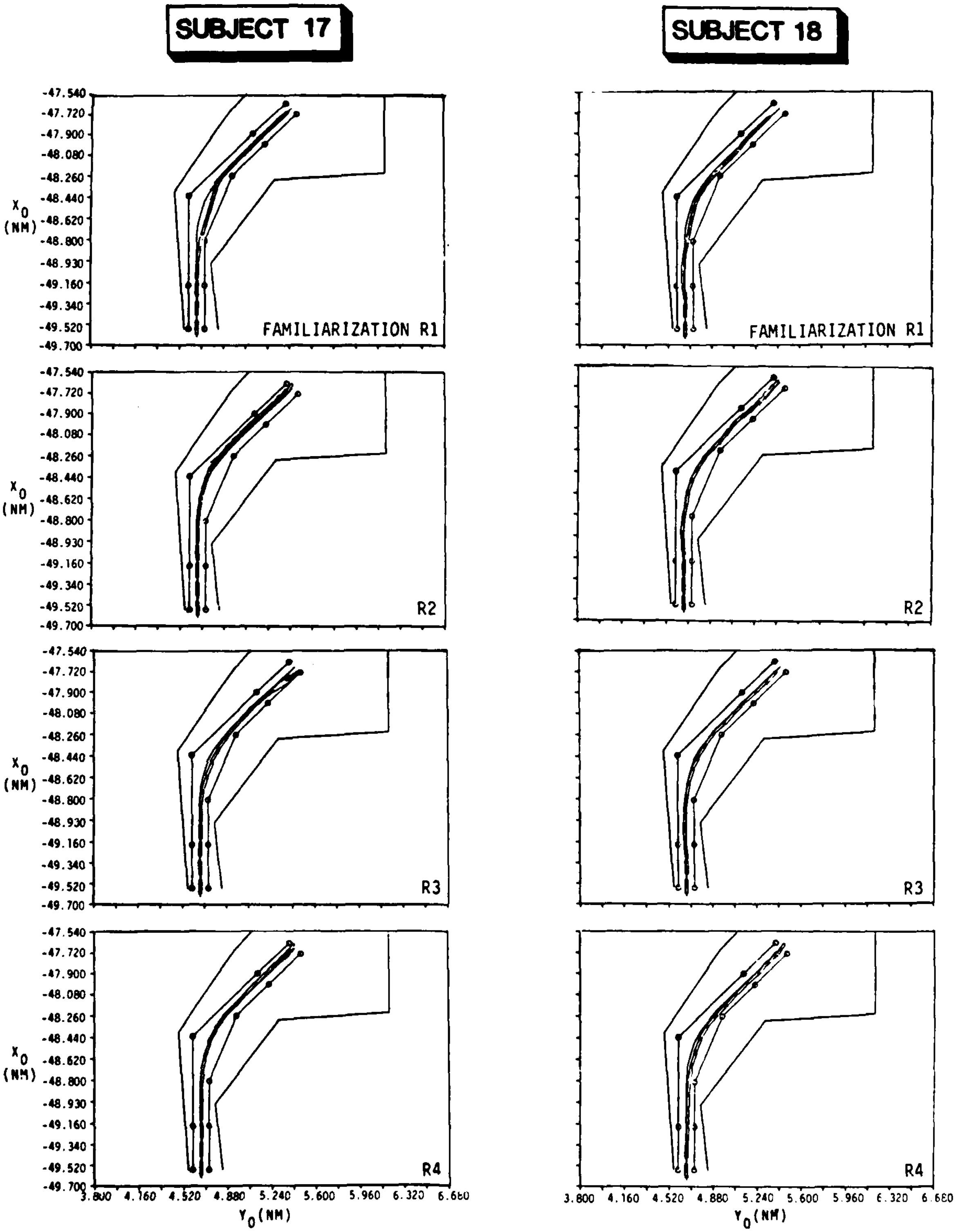


Figure 3-4I. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S17 and S18

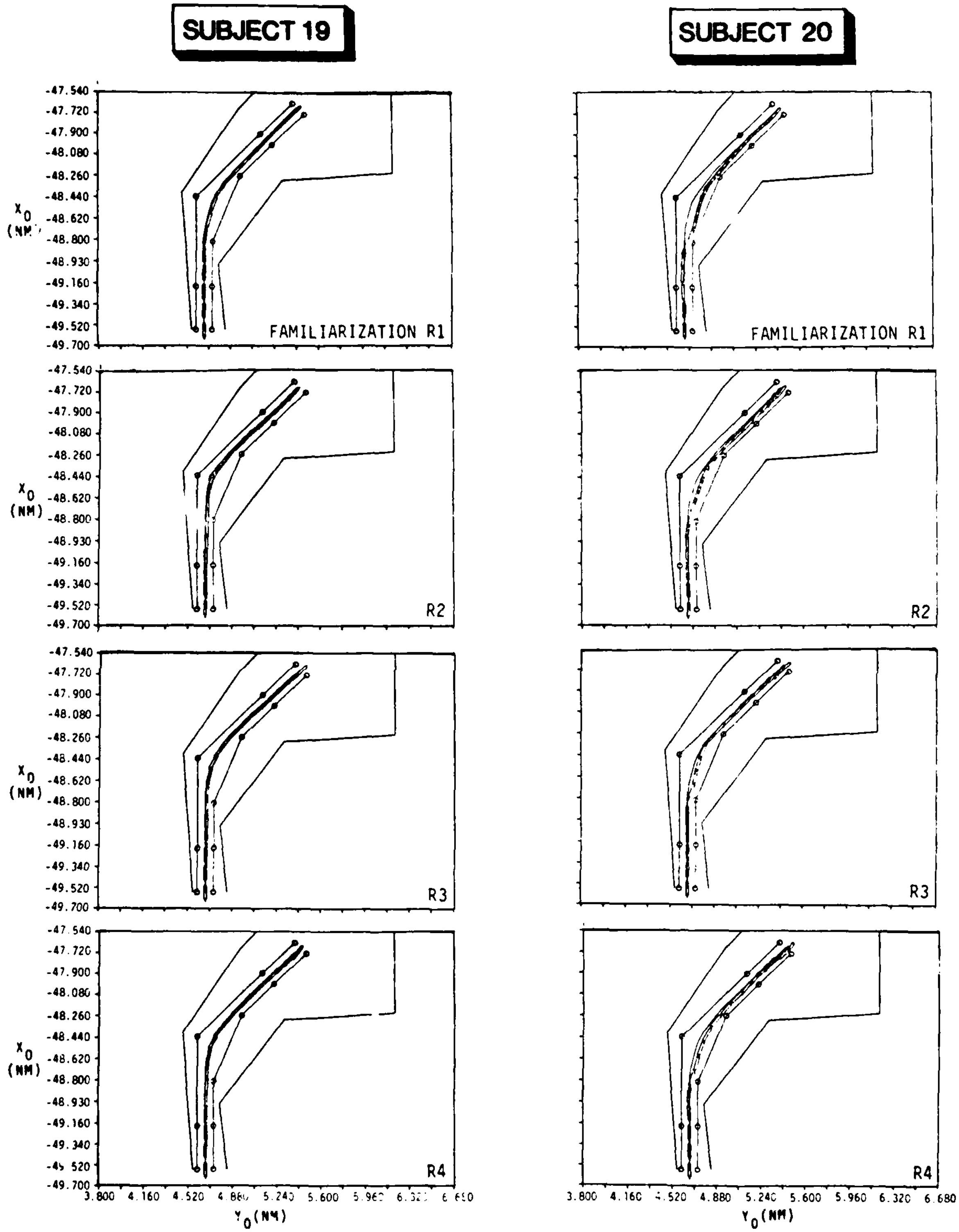


Figure 3-4J. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S19 and S20

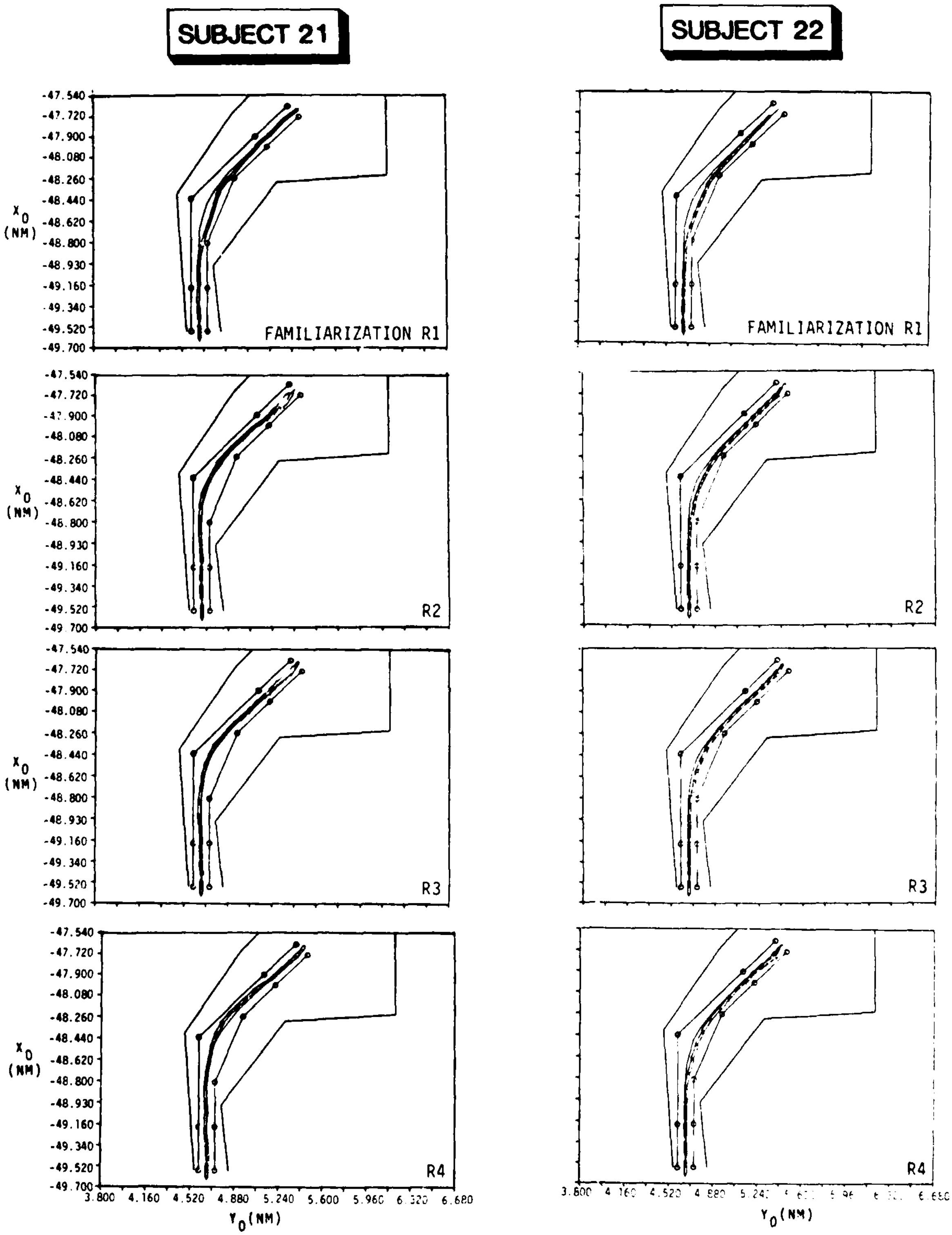


Figure 3-4K. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S21 and S22

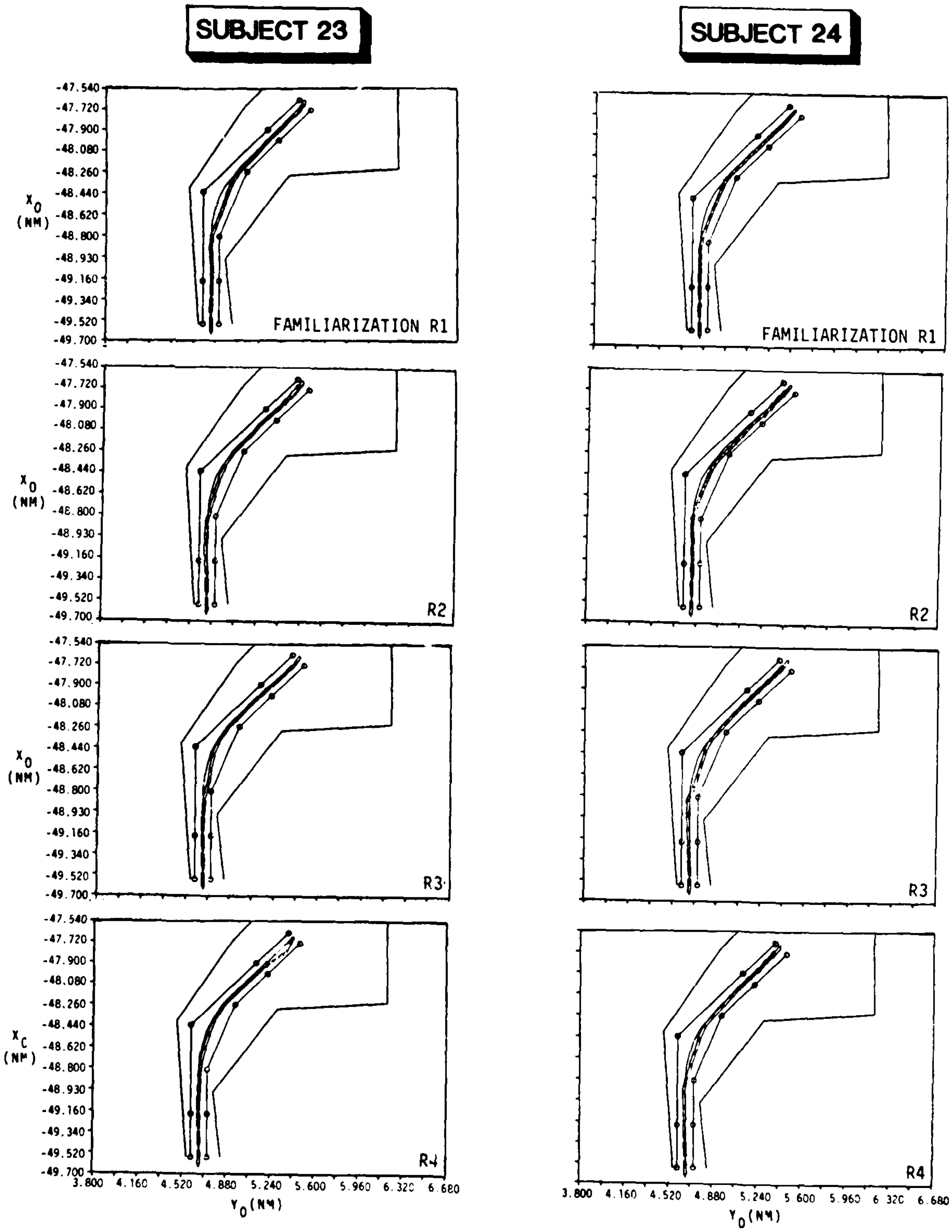


Figure 3-4L. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S23 and S24

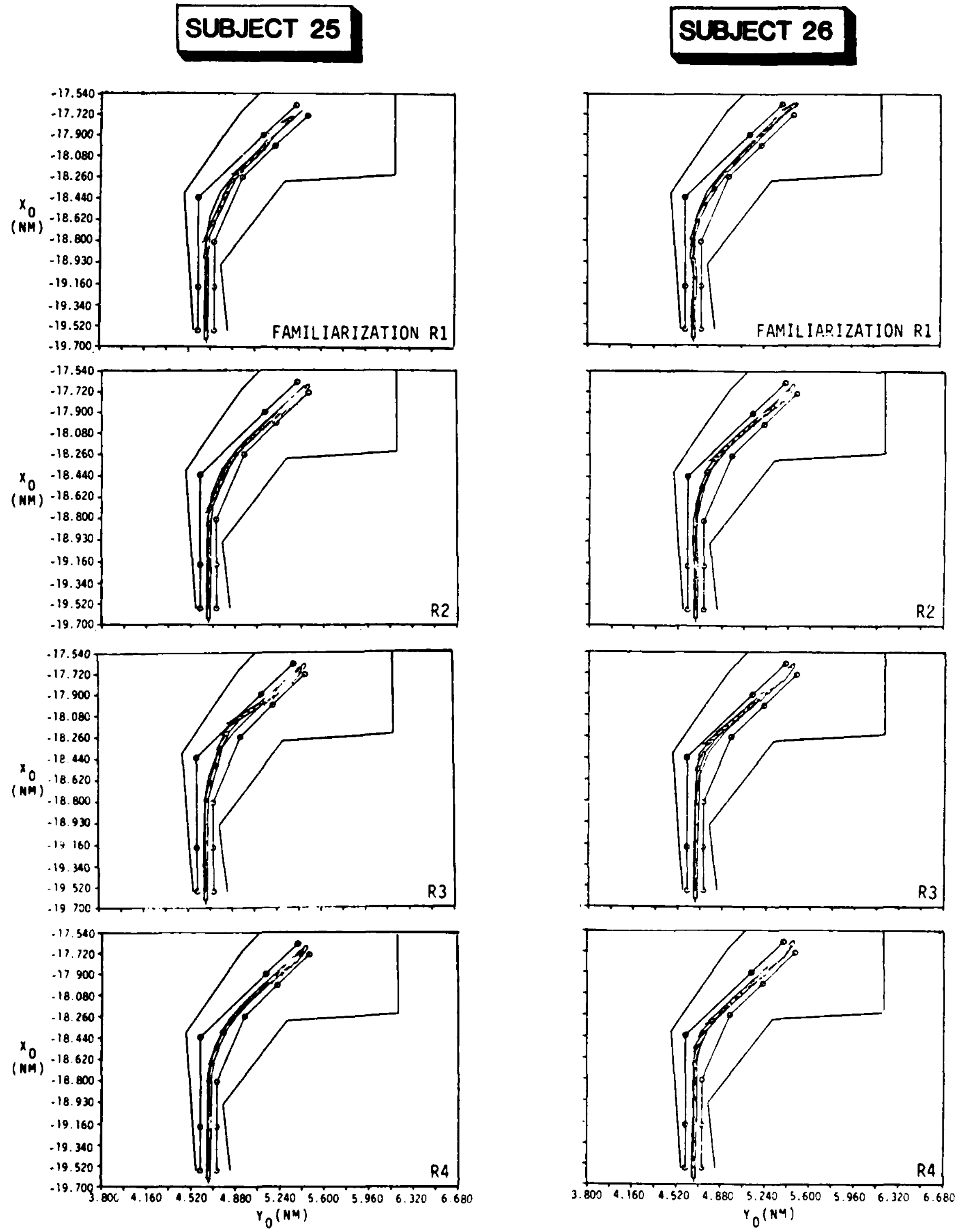


Figure 3-4M. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S25 and S26

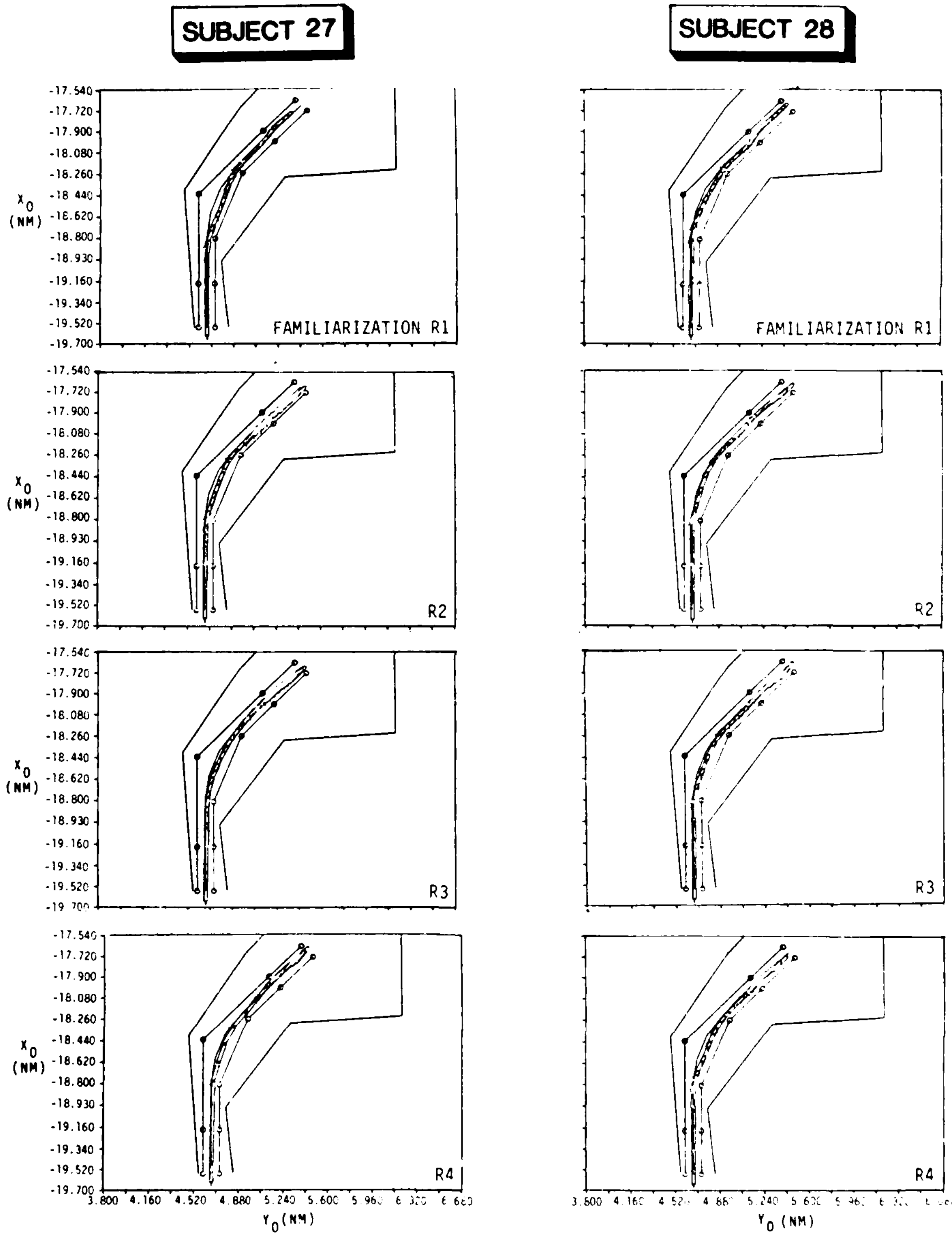


Figure 3-4N. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S27 and S28

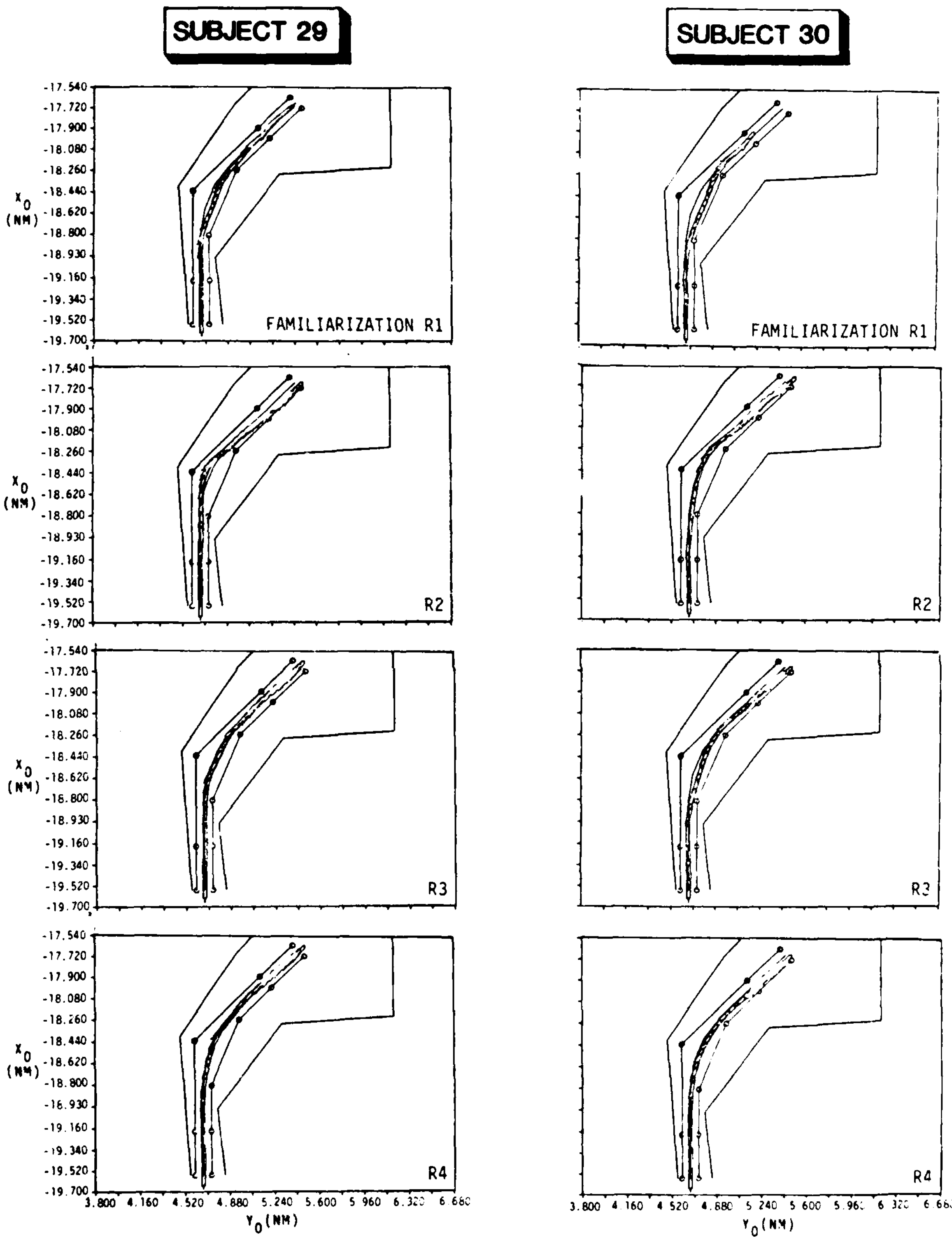


Figure 3-40. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S29 and S30

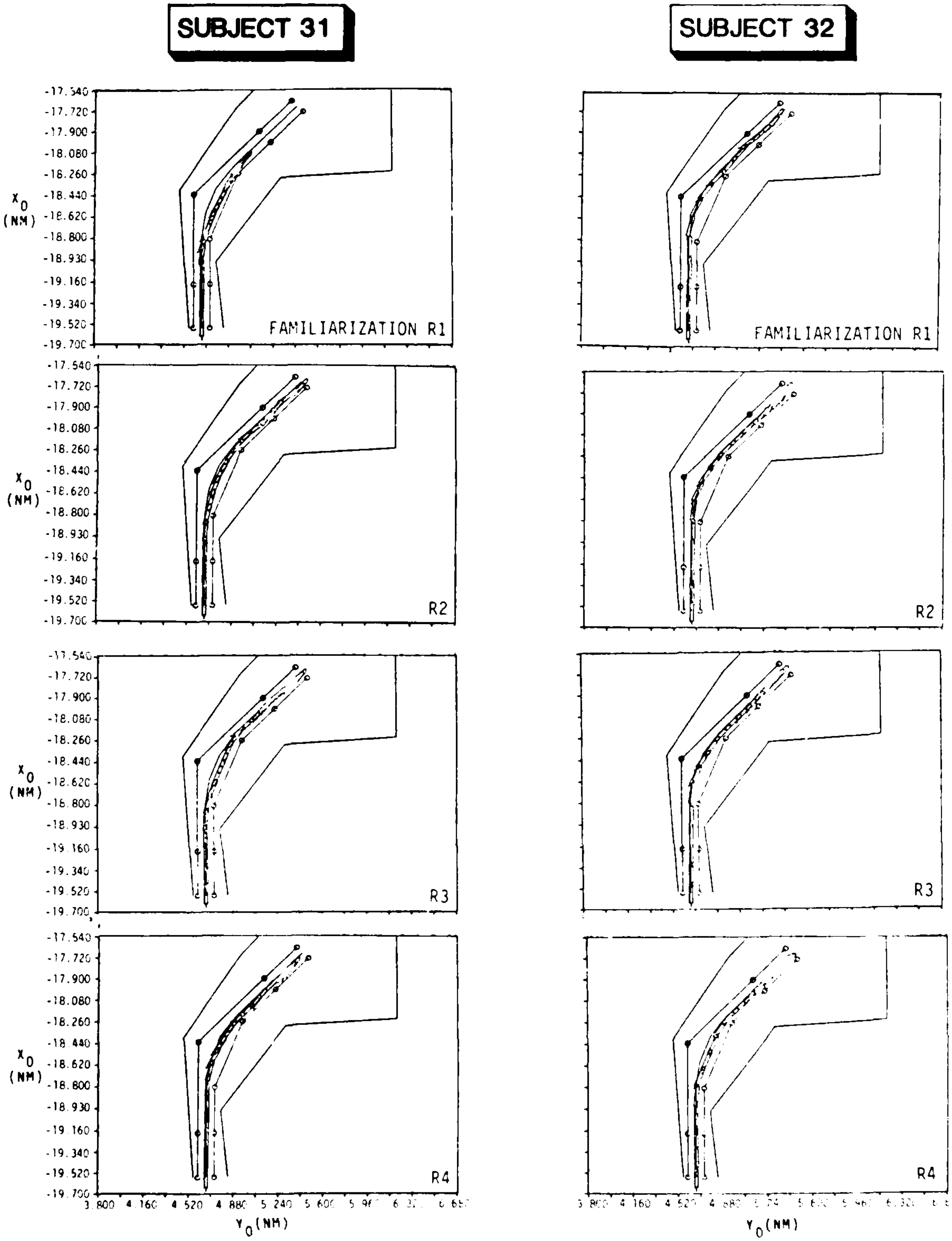


Figure 3-4P. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S31 and S32

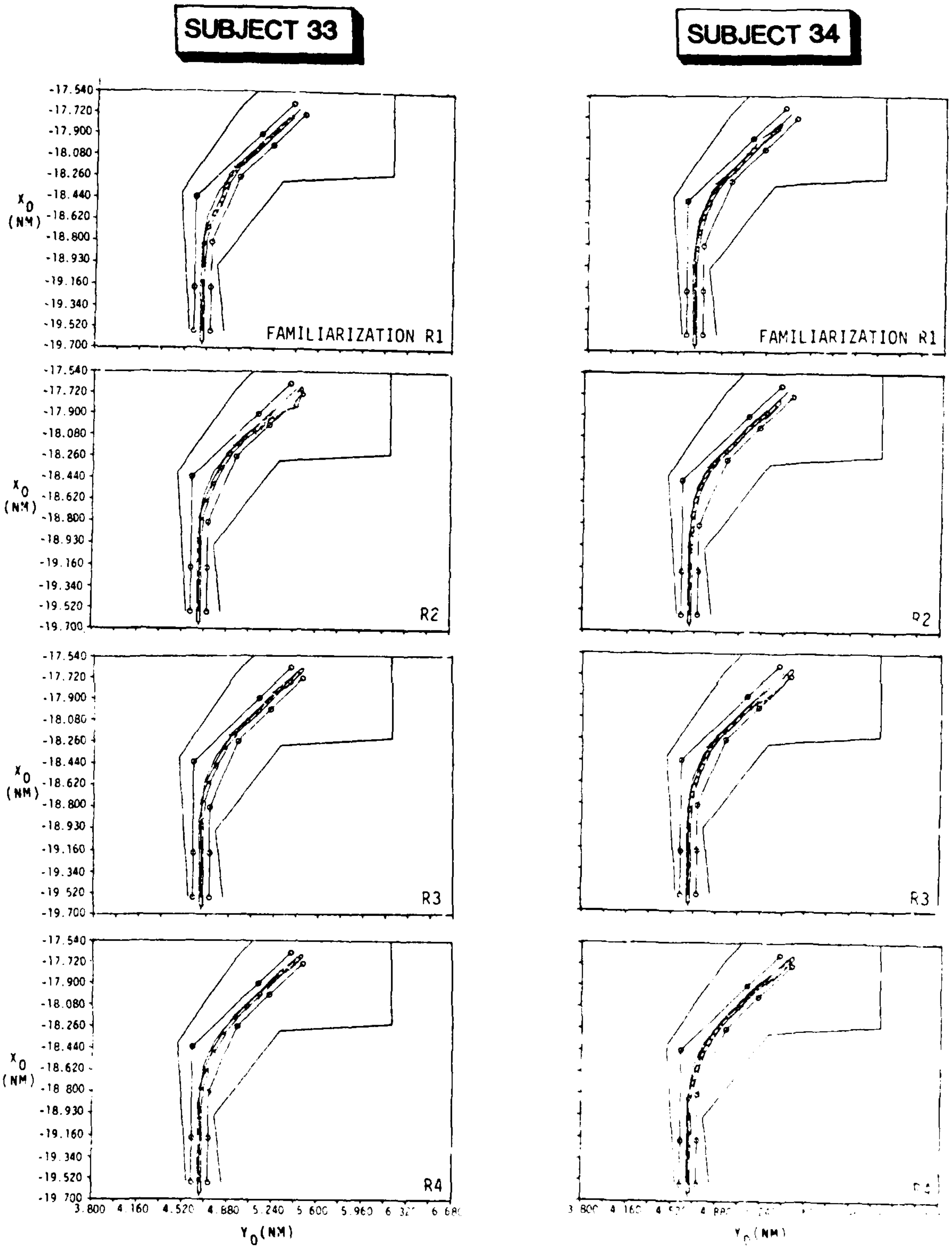


Figure 3-4Q. *Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4). Subjects S33 and S34*

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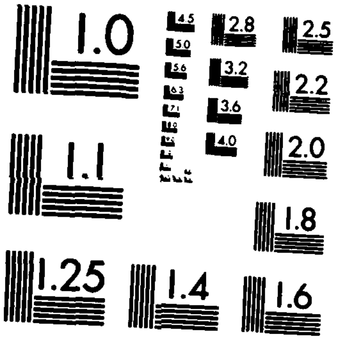

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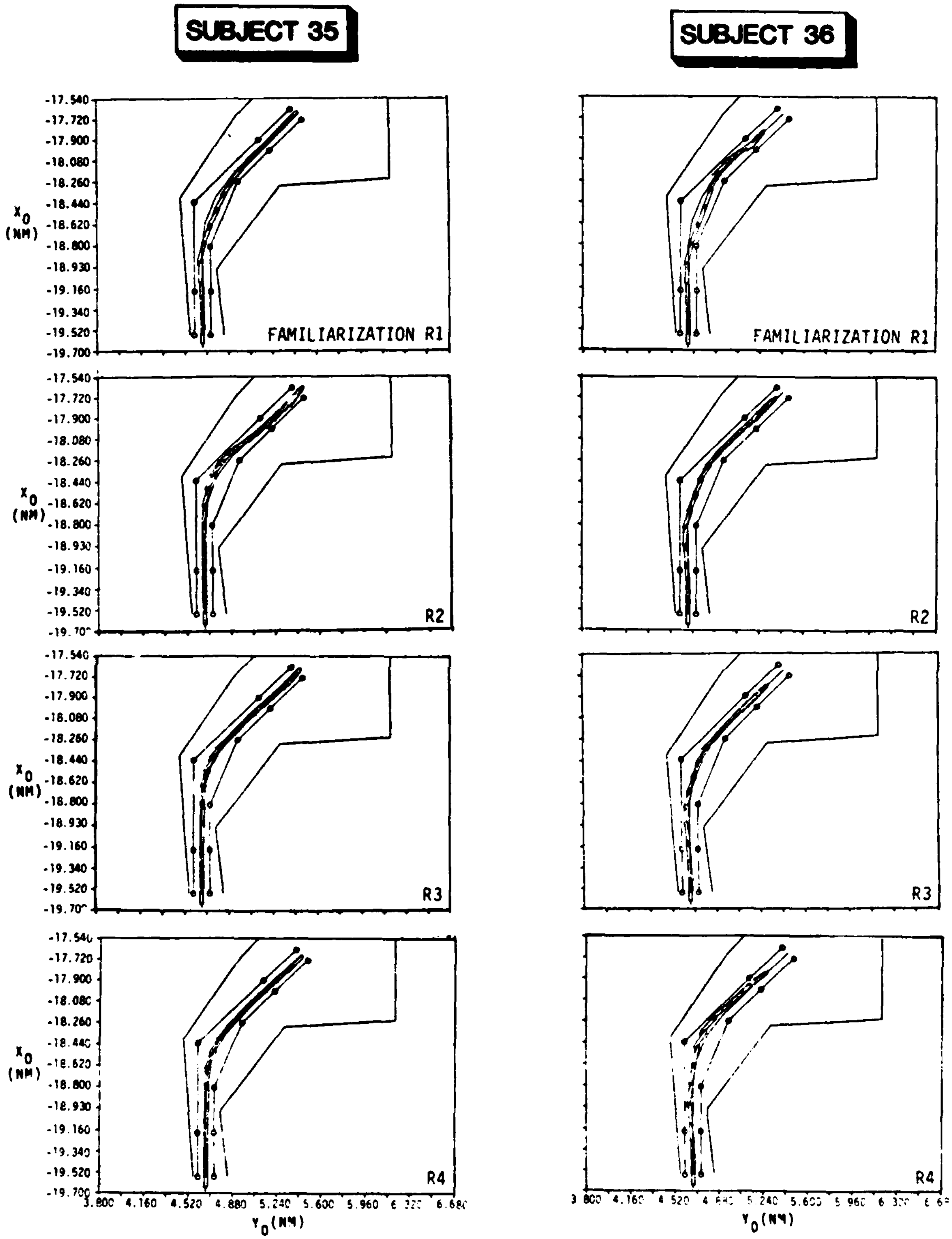


Figure 3-4R. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S35 and S36

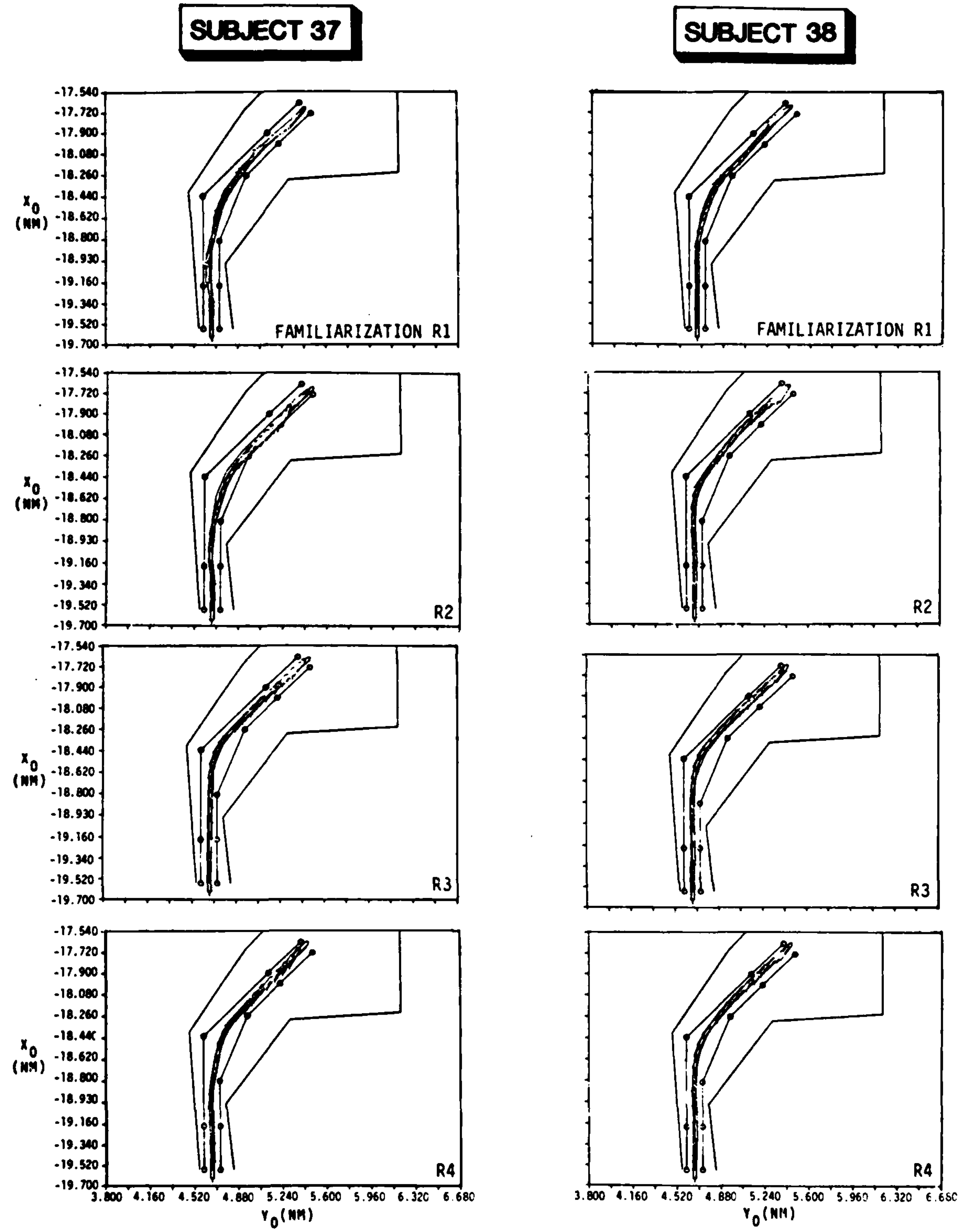


Figure 3-4S. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S37 and S38

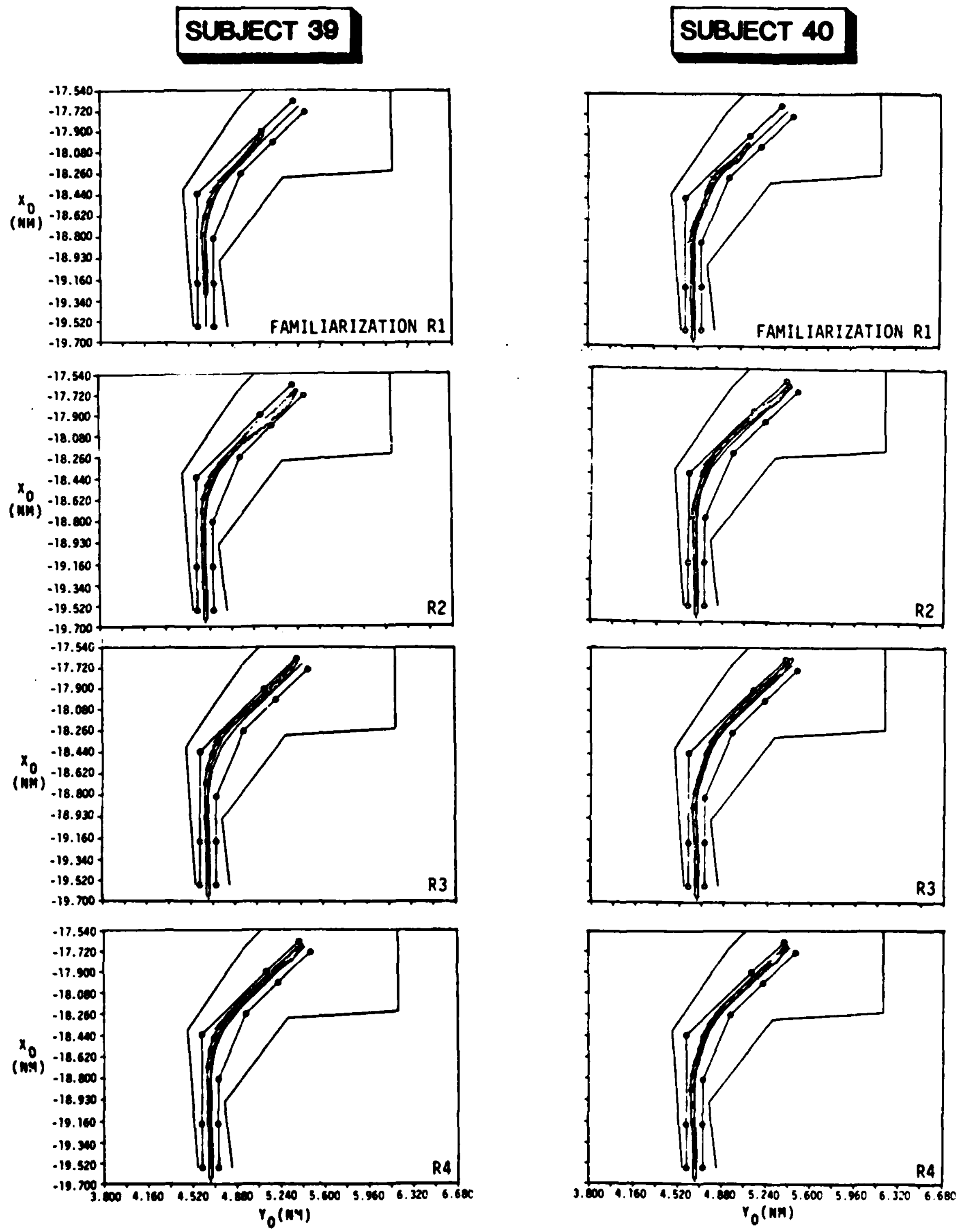


Figure 3-4T. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S39 and S40

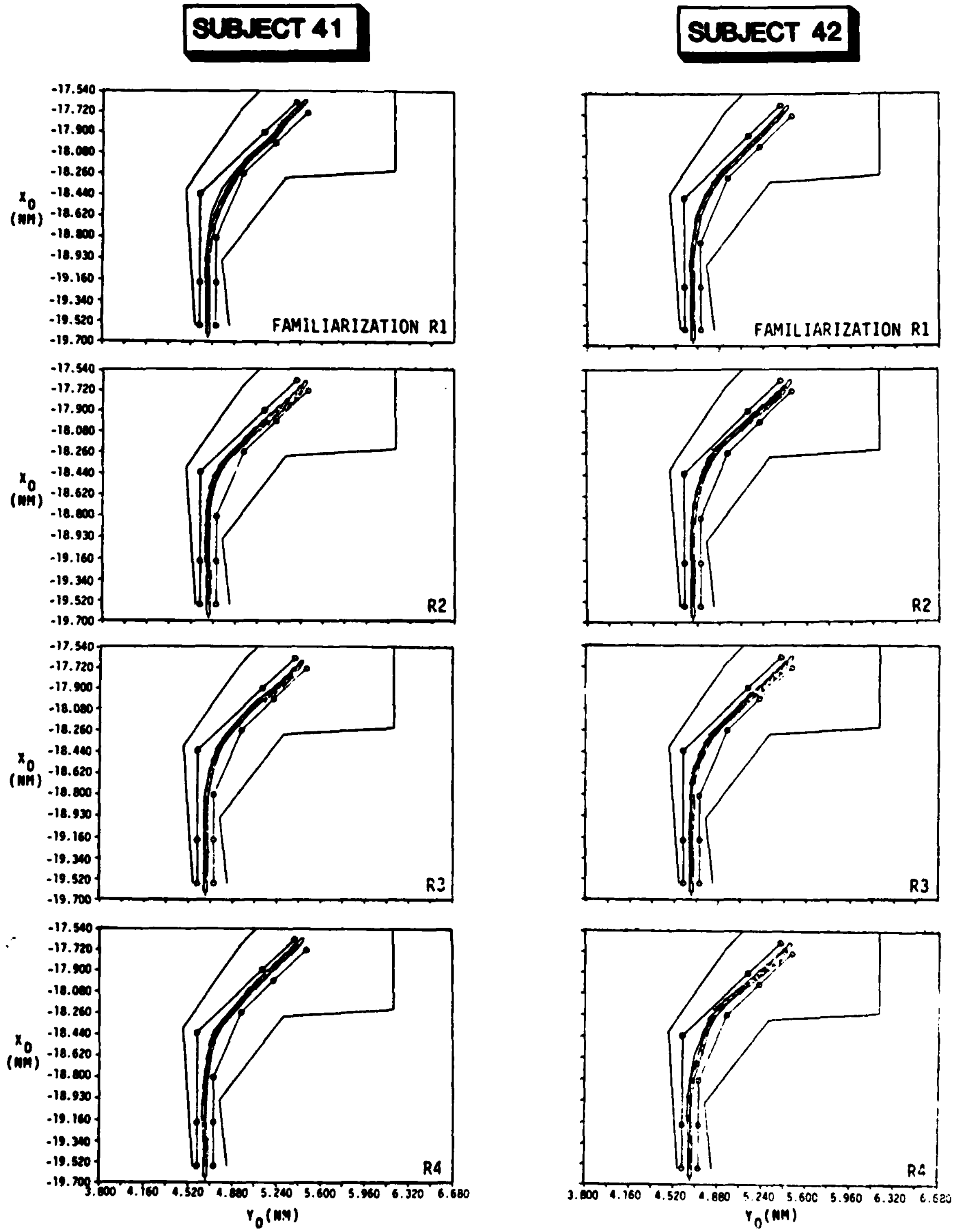


Figure 3-4U. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S41 and S42

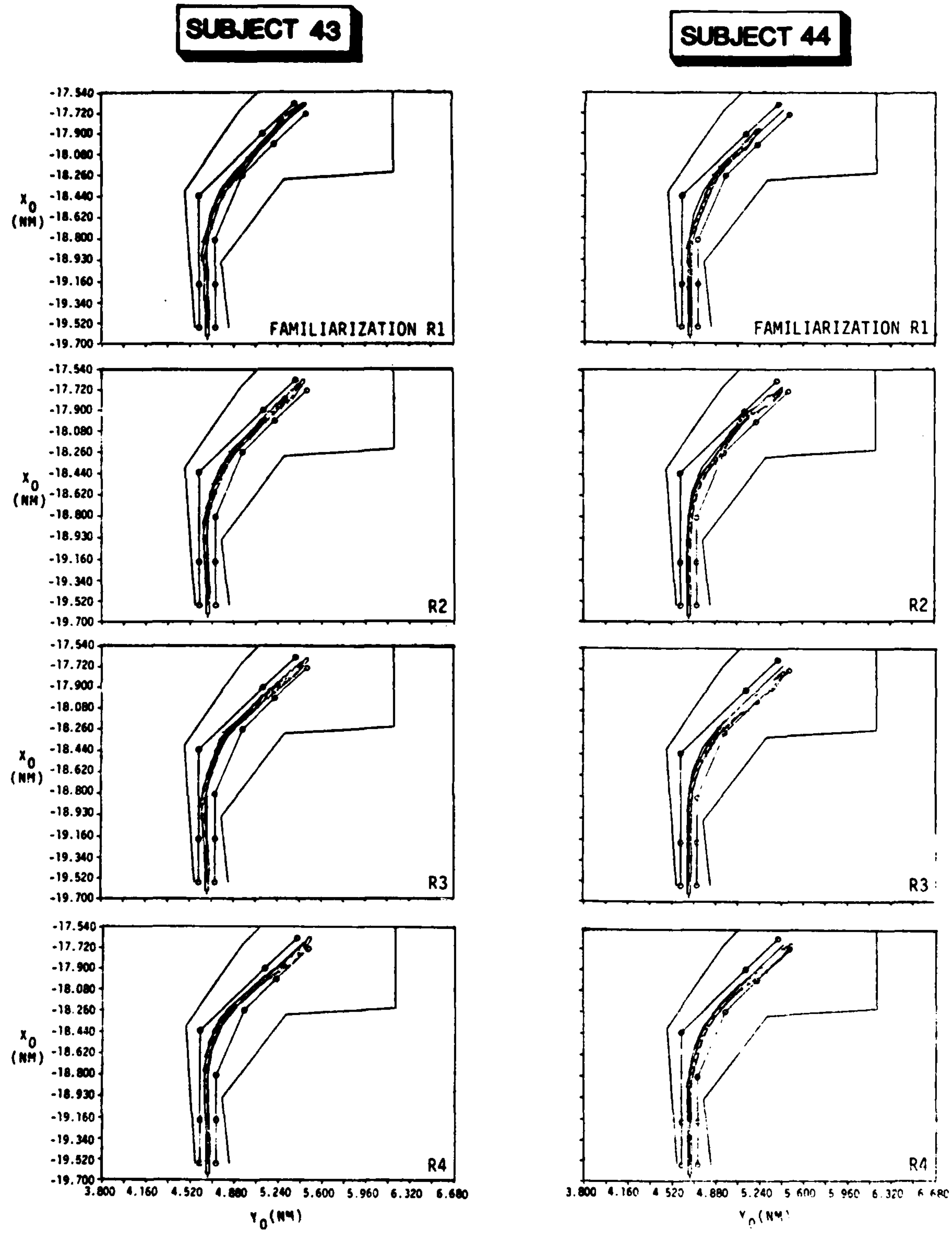


Figure 3-4V. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S43 and S44

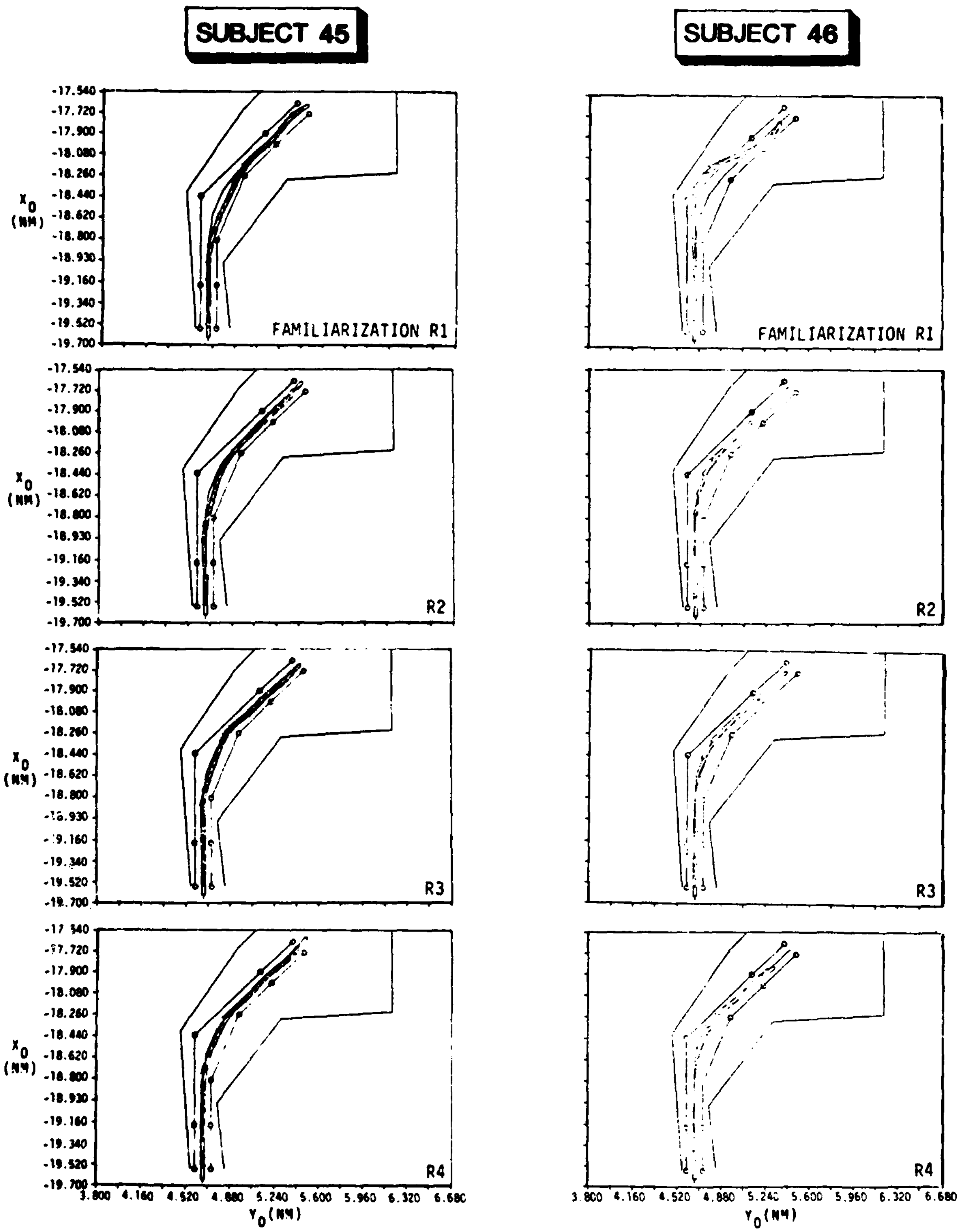


Figure 3-4W. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S45 and S46

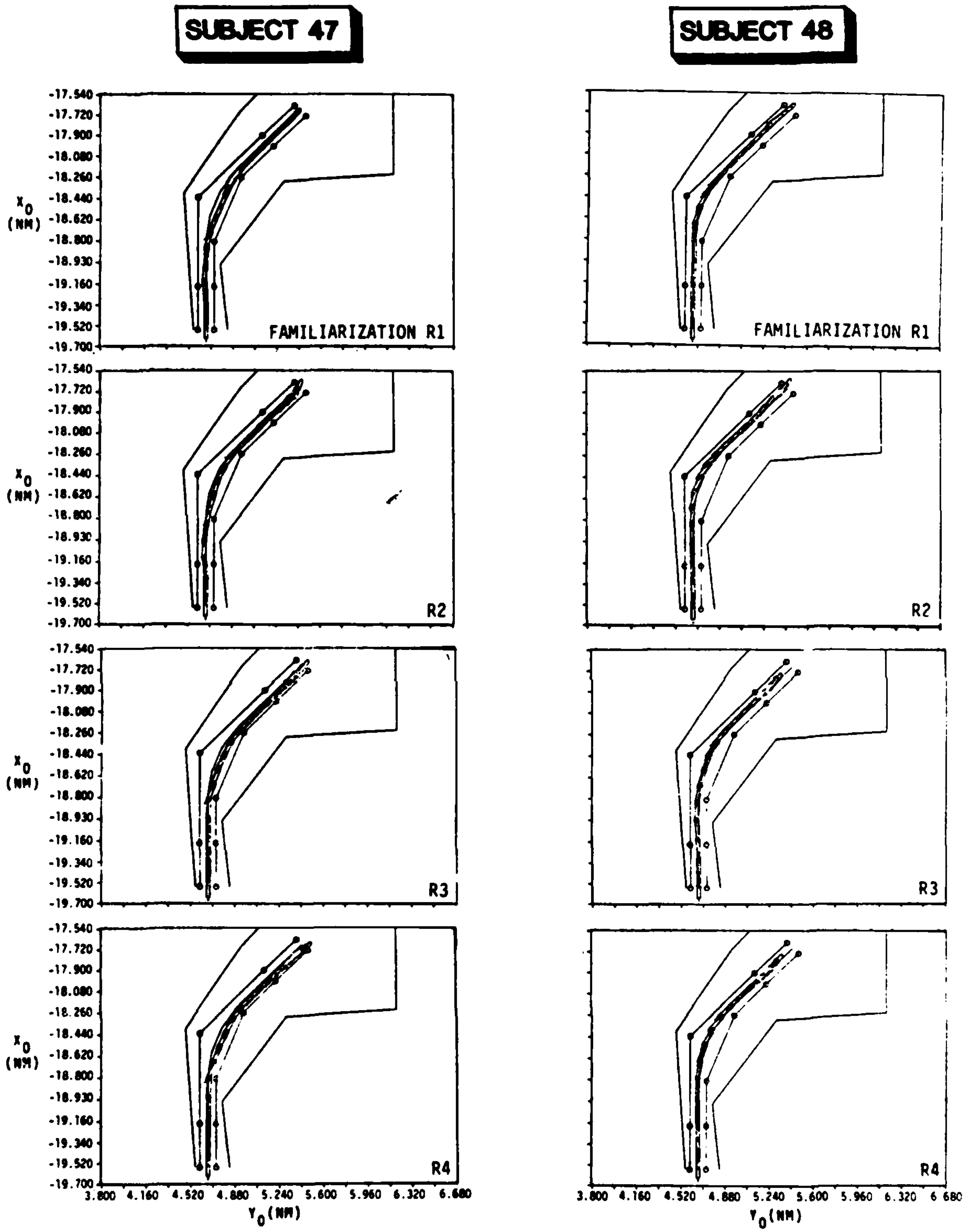


Figure 3-4X. Ship Tracks During Familiarization Run (R1) and Three Replicates (R2, R3, R4): Subjects S47 and S48

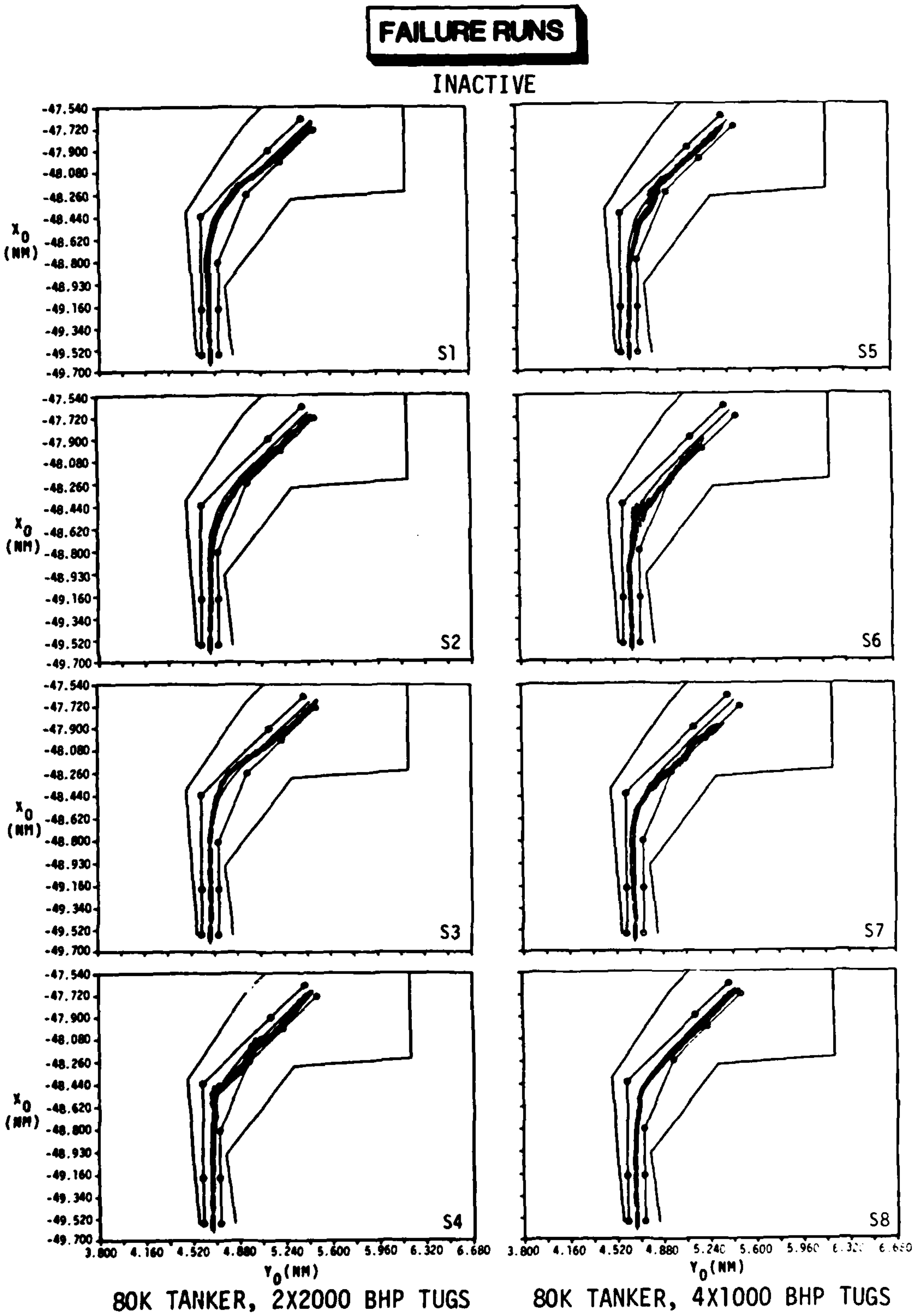


Figure 3-5A. Ship Tracks During Failure Run (R5) - Subjects S1 to S8

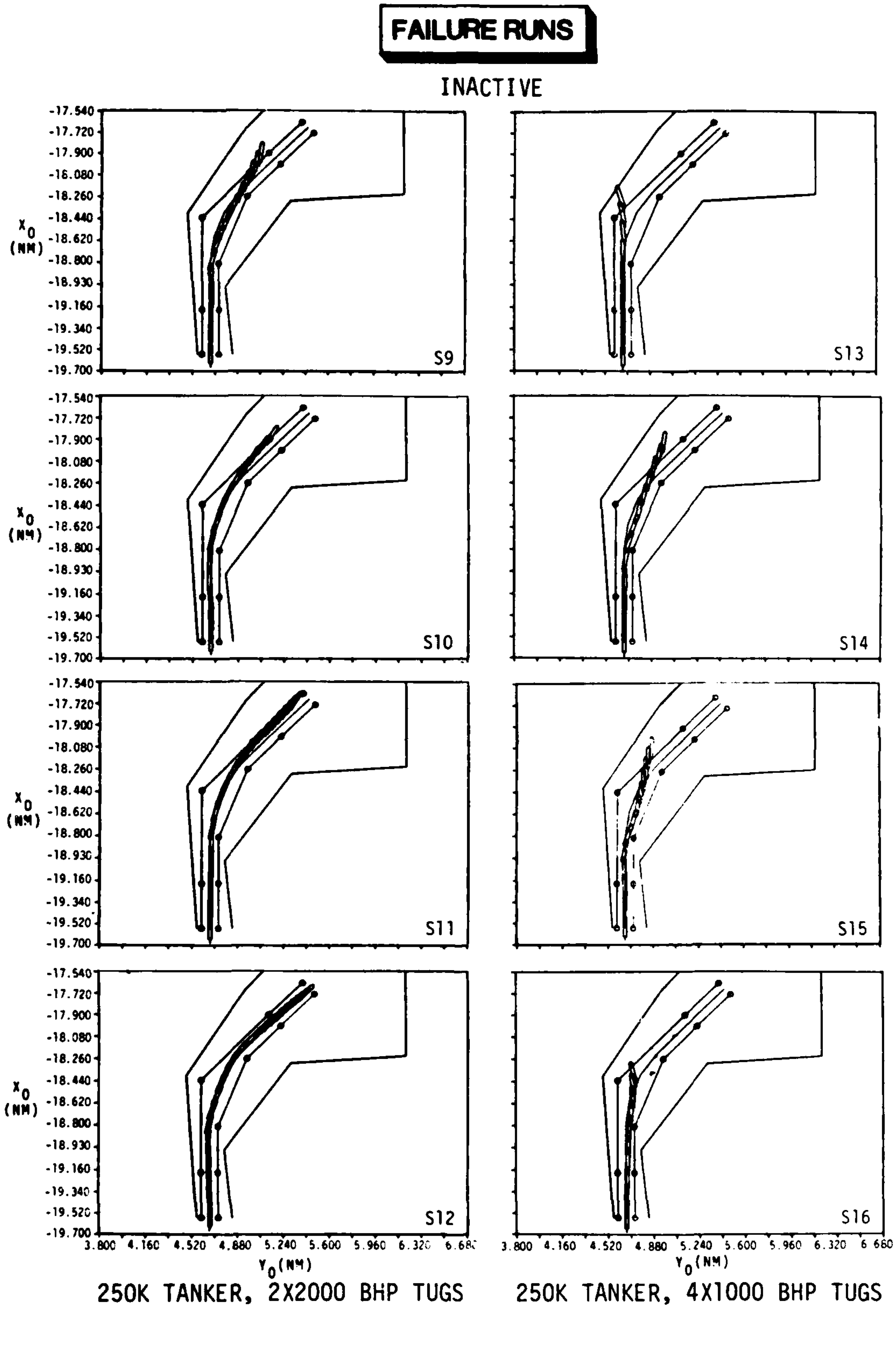


Figure 3-5B. Ship Tracks During Failure Run (R5) - Subjects S9 to S16

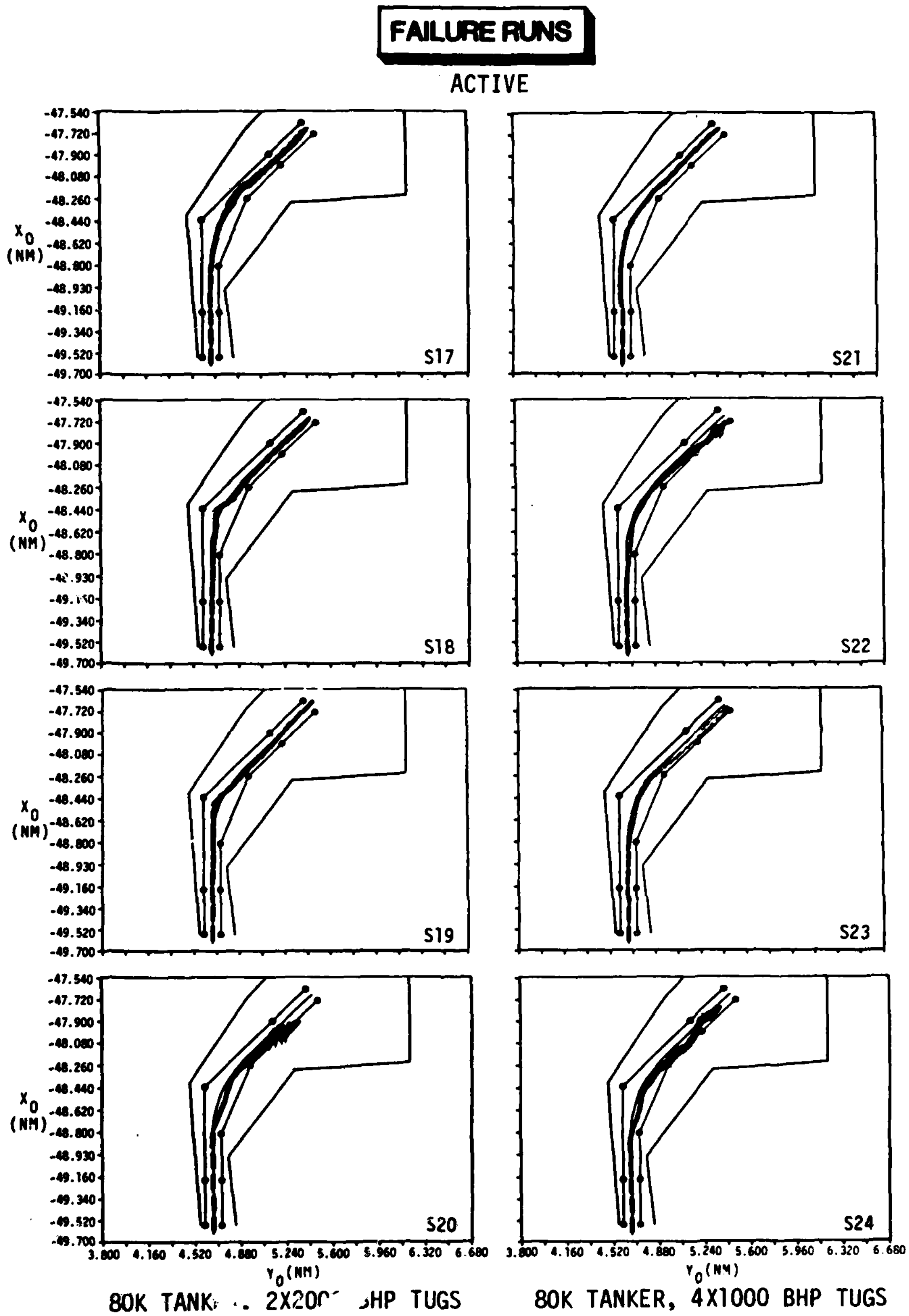


Figure 3-5C. Ship Tracks During Failure Run (R5) - Subjects S17 to S24

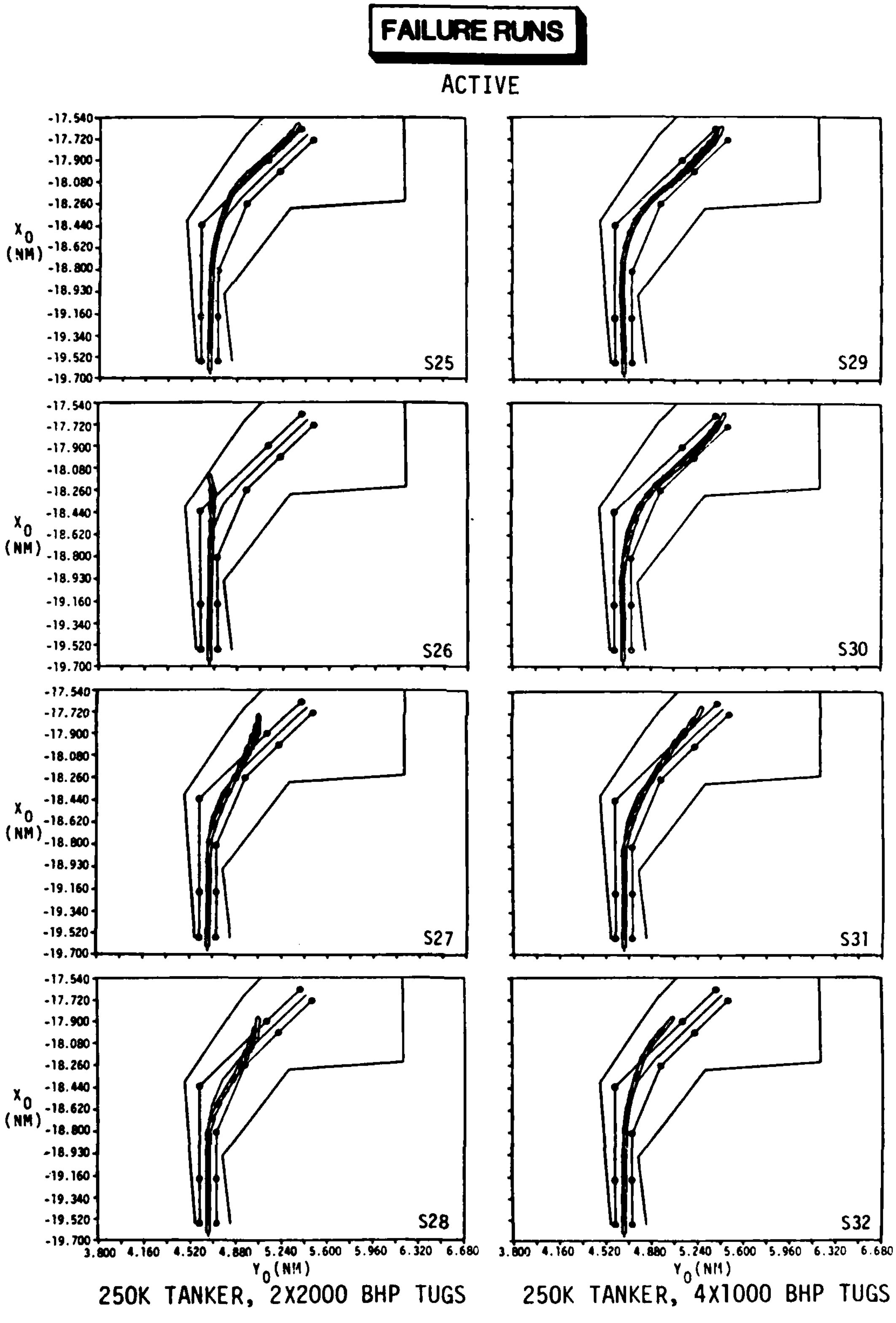
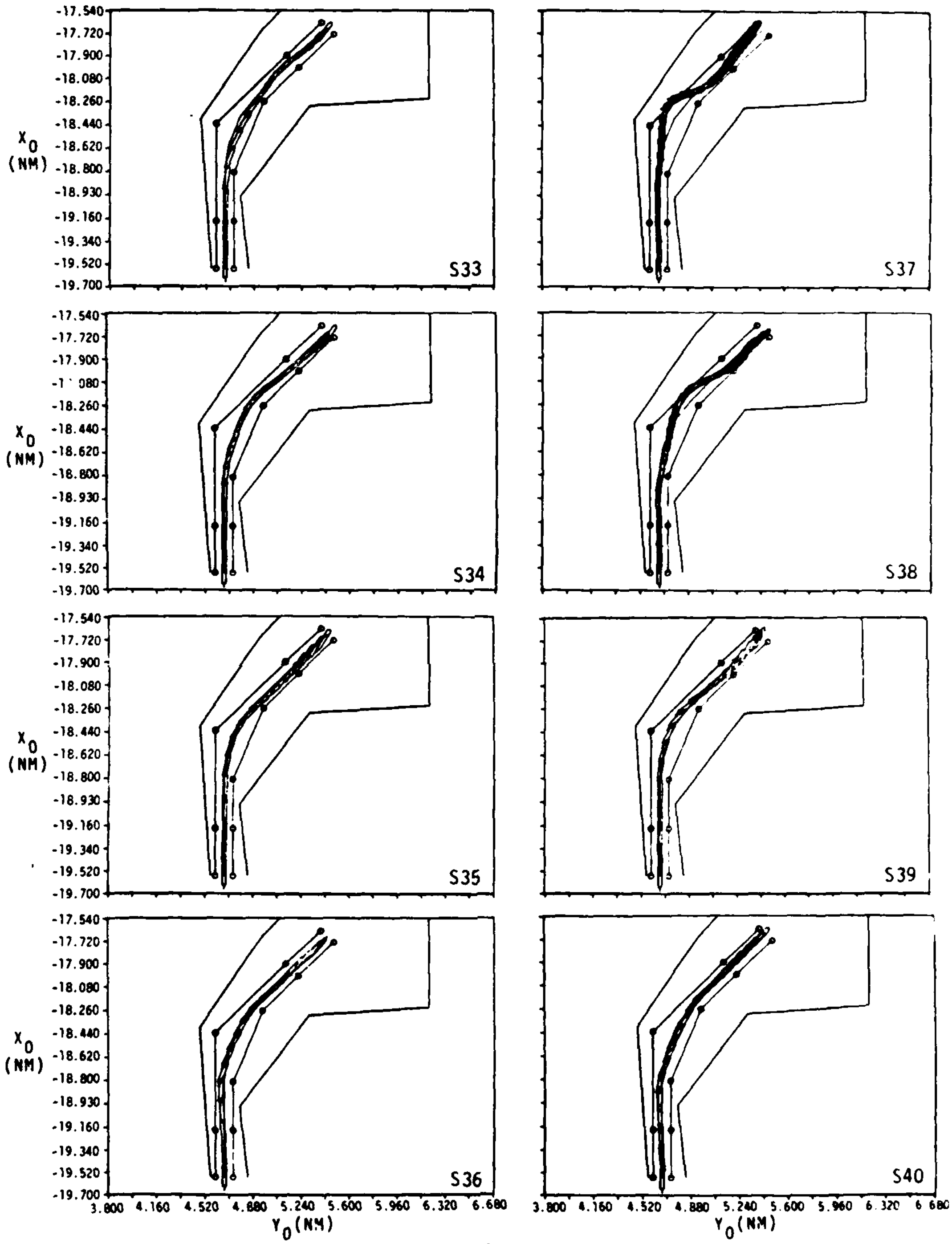


Figure 3-5D. Ship Tracks During Failure Run (R5) - Subjects S25 to S32

FAILURE RUNS

INACTIVE



250K TANKER, 2X4000 BHP TUGS

250K TANKER, 4X2000 BHP TUGS

Figure 3-5E. Ship Tracks During Failure Run (R5) - Subjects S33 to S40

FAILURE RUNS

ACTIVE

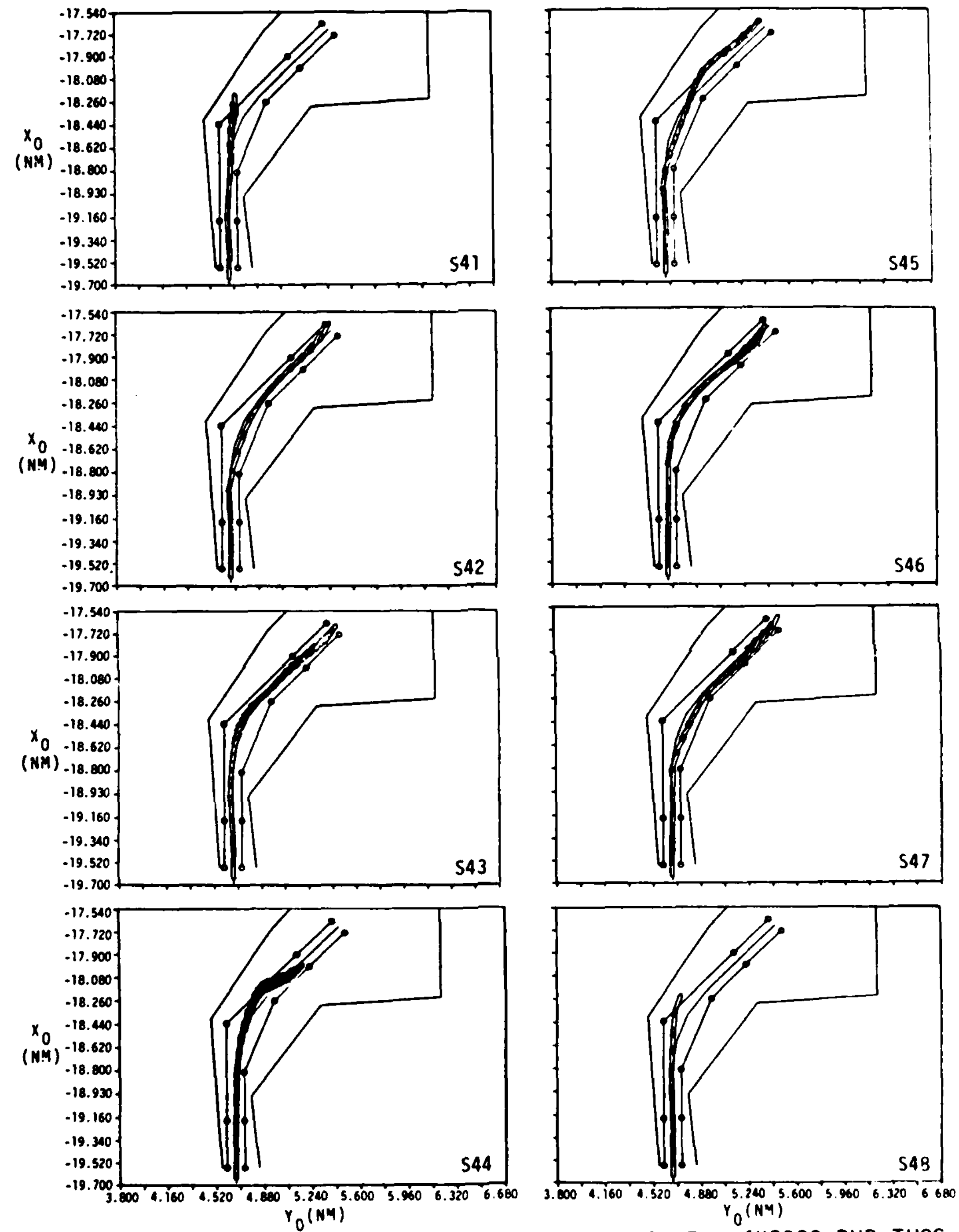


Figure 3-5F. Ship Tracks During Failure Run (R5) - Subjects S41 to S48

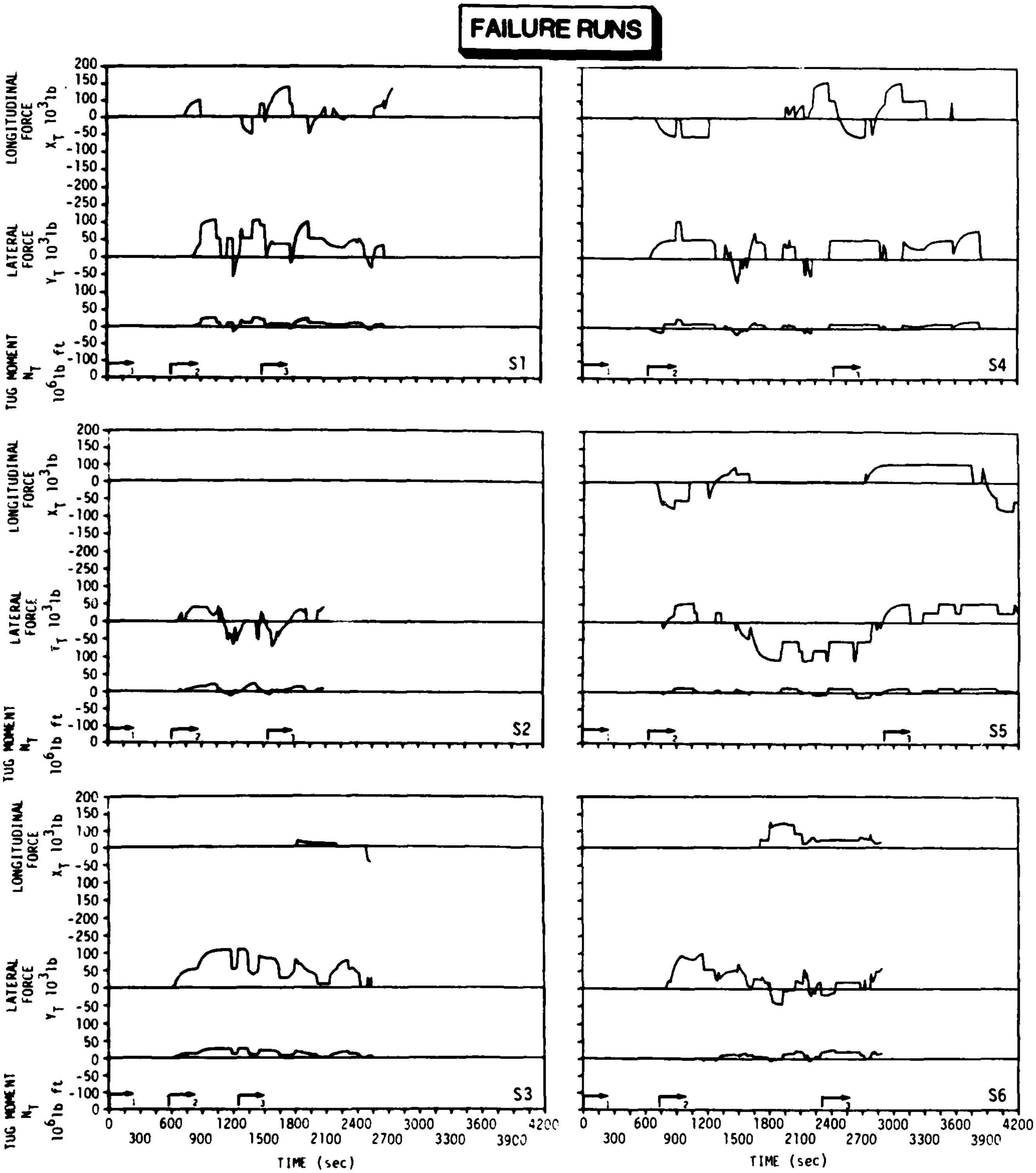
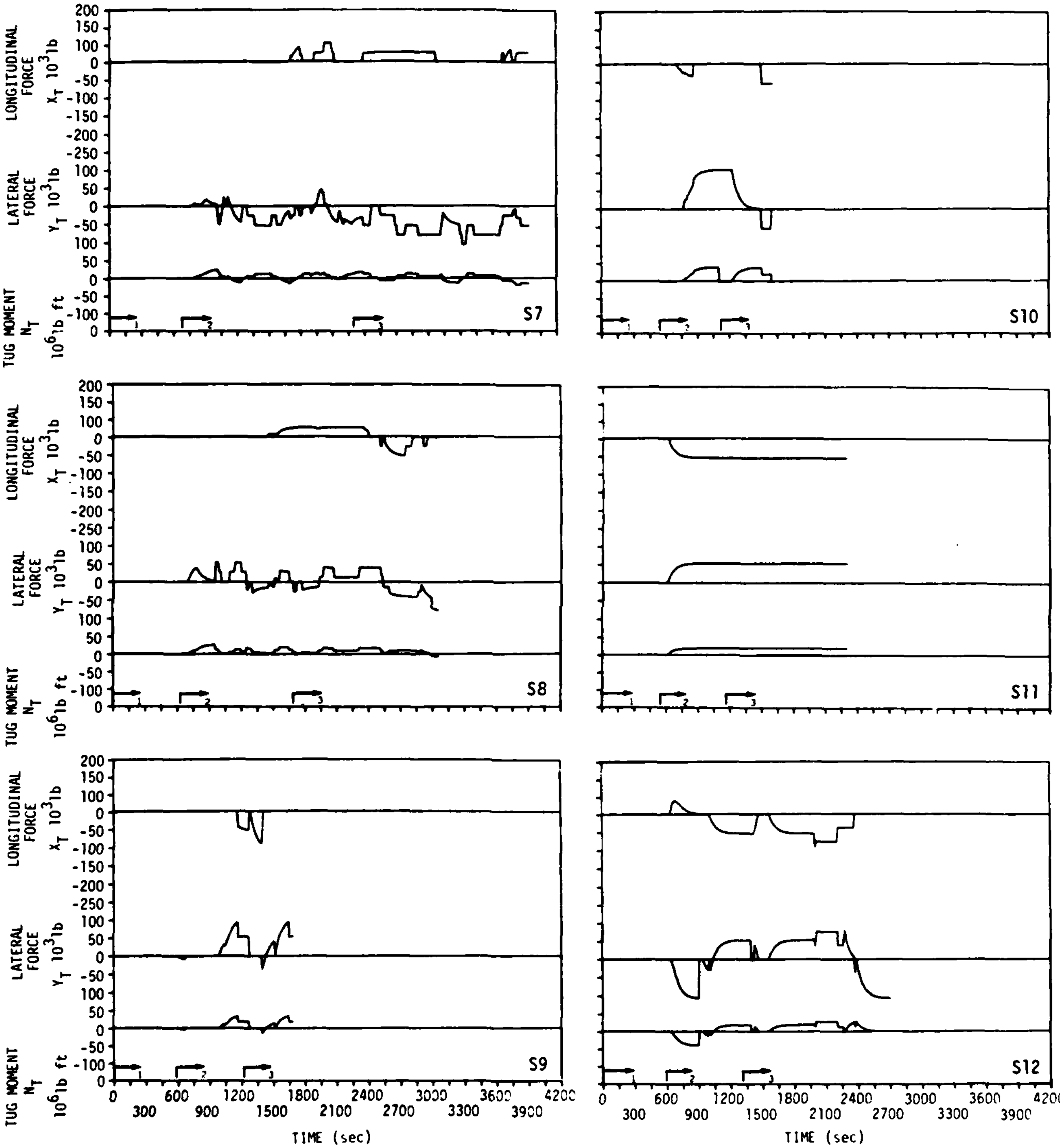


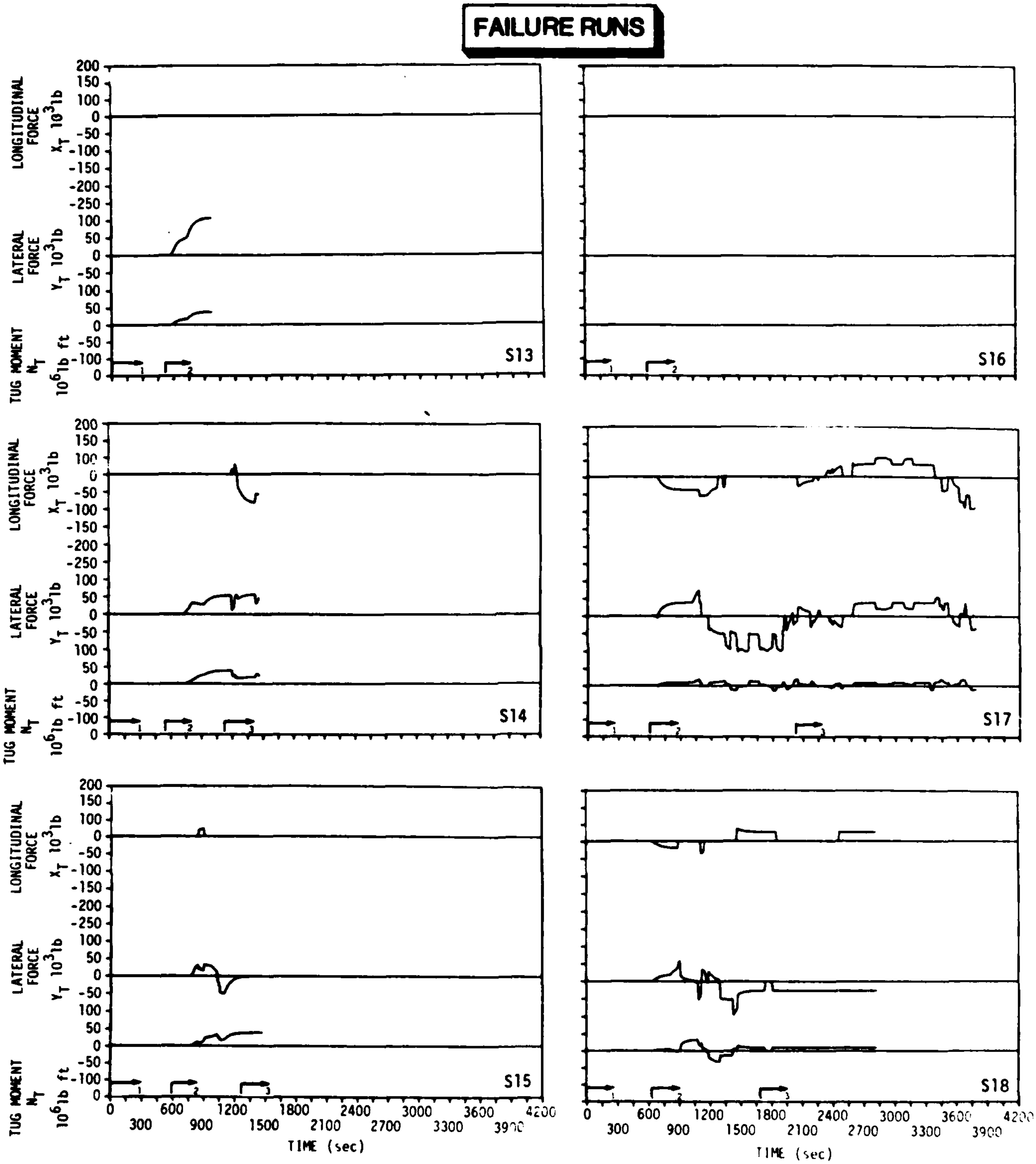
Figure 3-6A. Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S1 to S6

FAILURE RUNS



TUG FORCES (X_T, Y_T) AND MOMENTS (N_T)

Figure 3-6B. Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S7 to S12



TUG FORCES (X_T, Y_T) AND MOMENTS (N_T)

Figure 3-6C. ***Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S13 to S18***

FAILURE RUNS

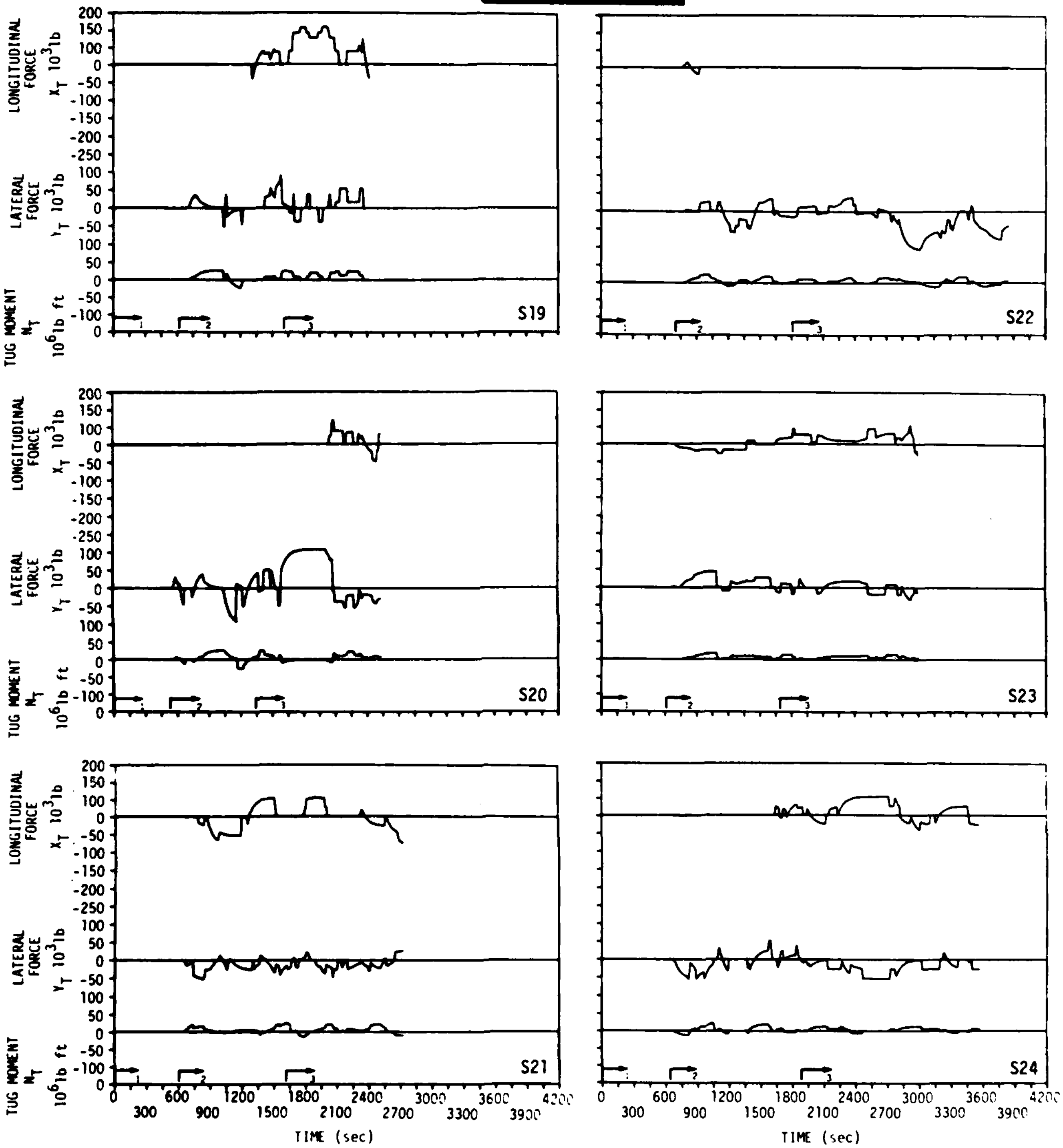


***Figure 3-6D.** Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S19 to S24*

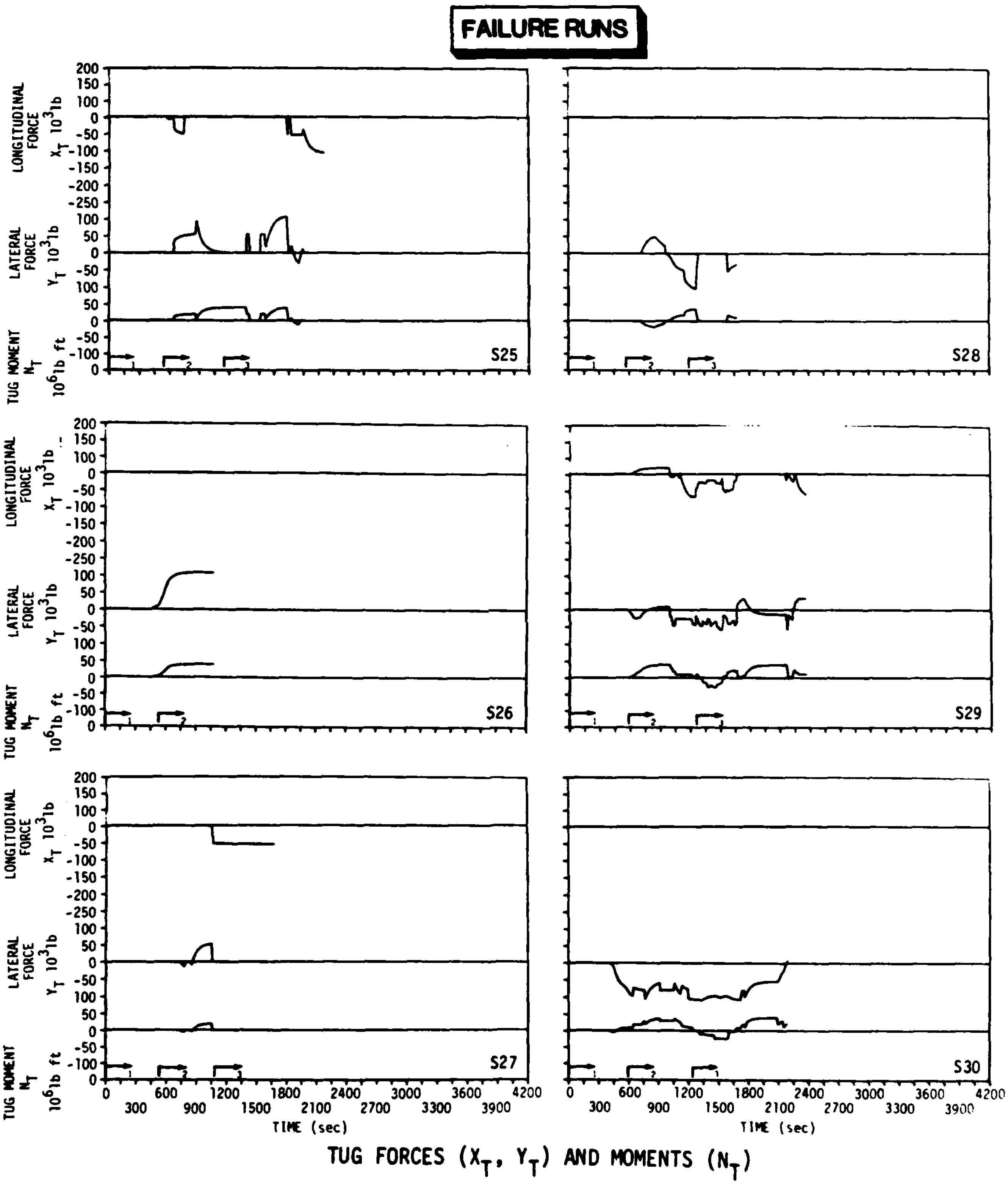
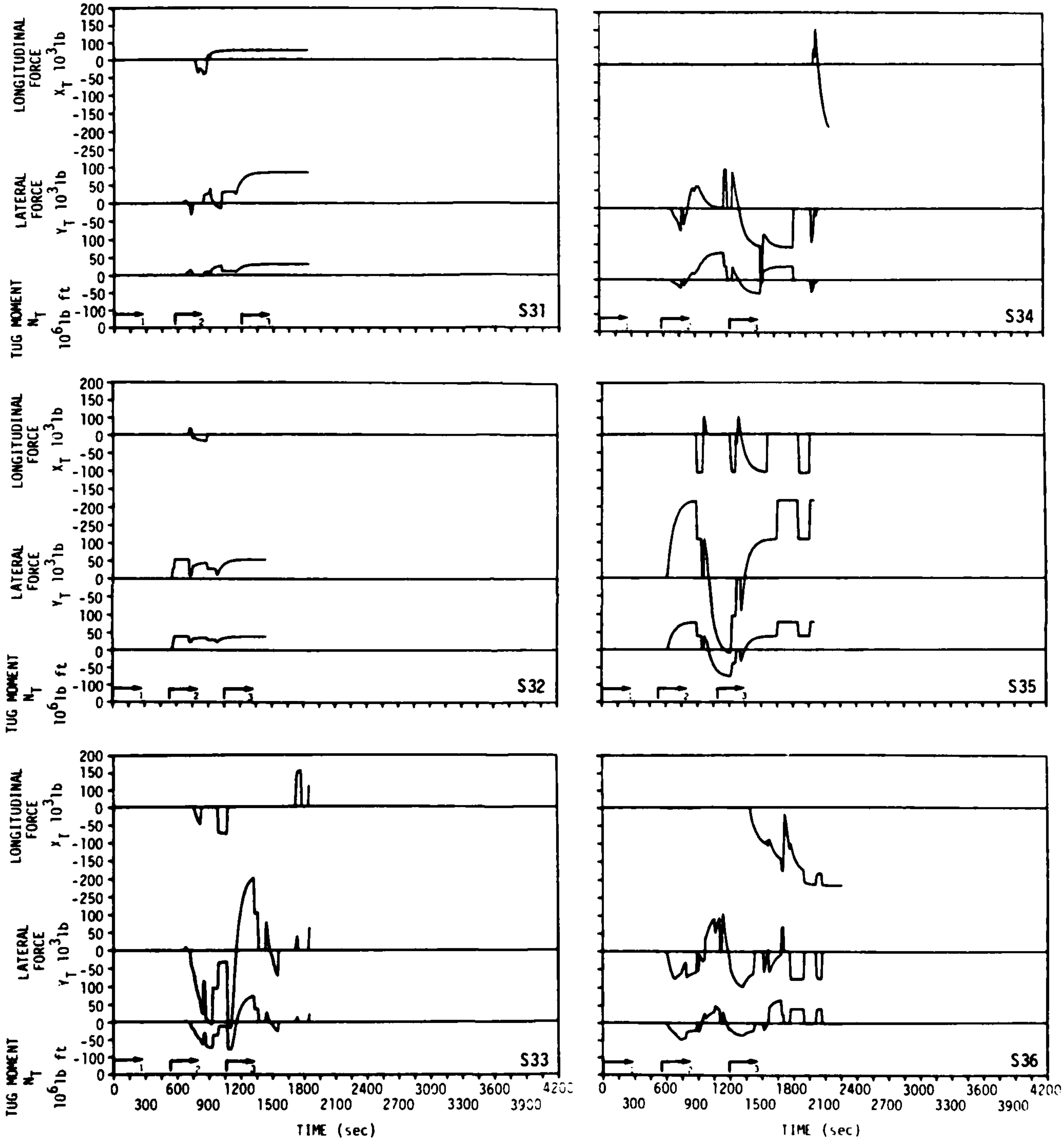


Figure 3-6E. Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S25 to S30

FAILURE RUNS



TUG FORCES (X_T, Y_T) AND MOMENTS (N_T)

Figure 3-6F. Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S31 to S36

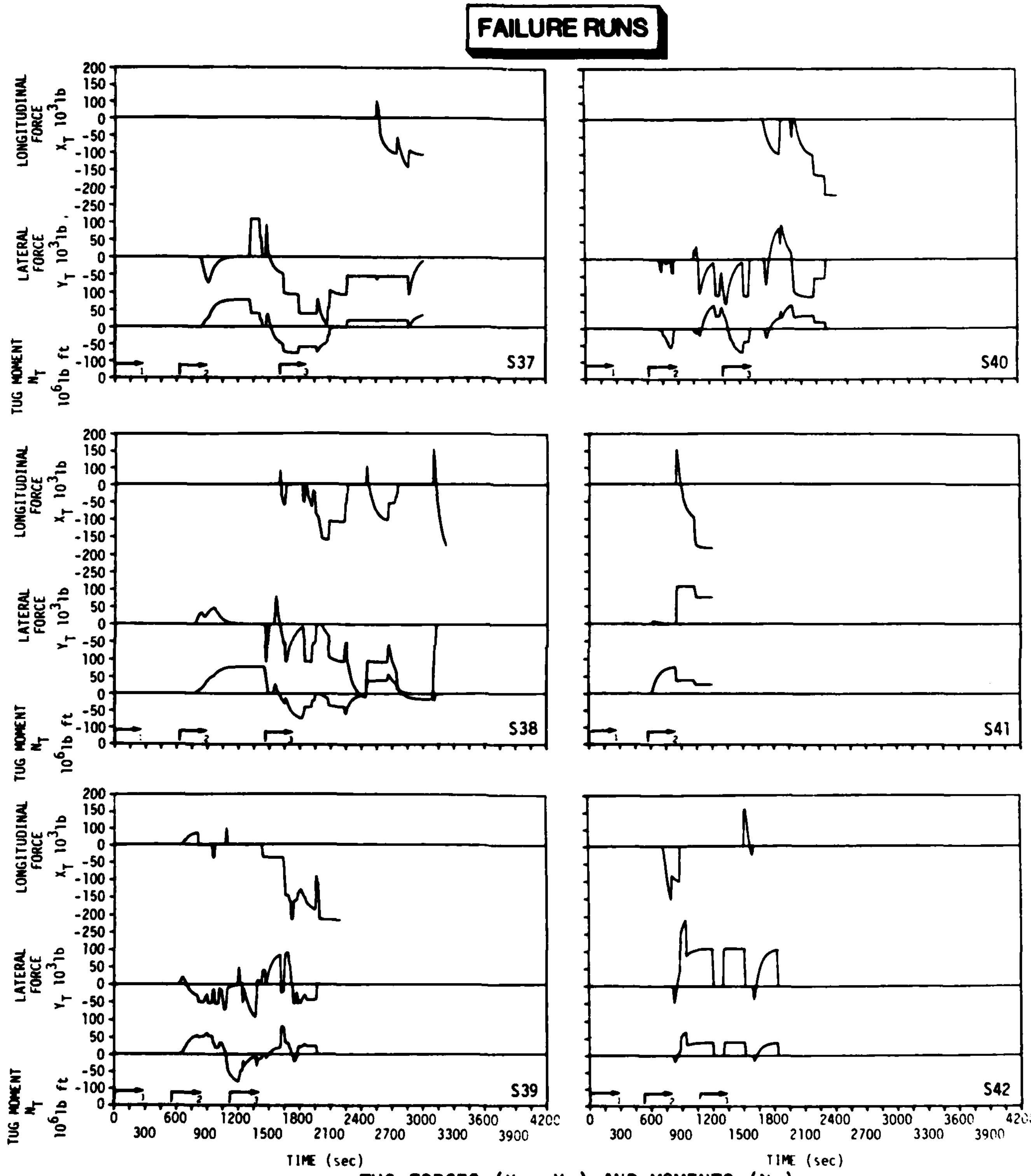


Figure 3-6G. Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S37 to S42

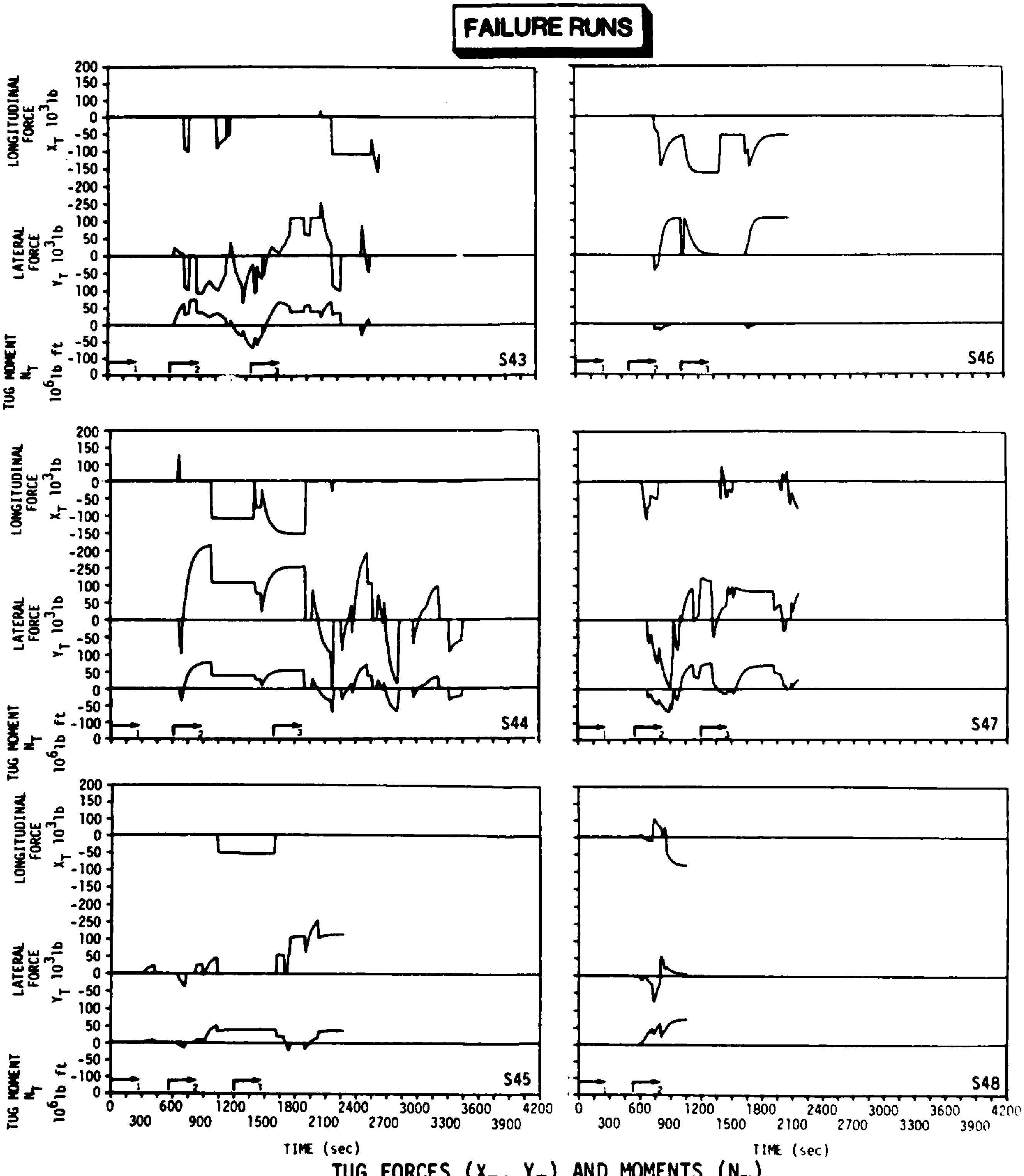


Figure 3-6H. Time Variation of Tug Forces and Moments During Failure Run (R5) - Subjects S43 to S48

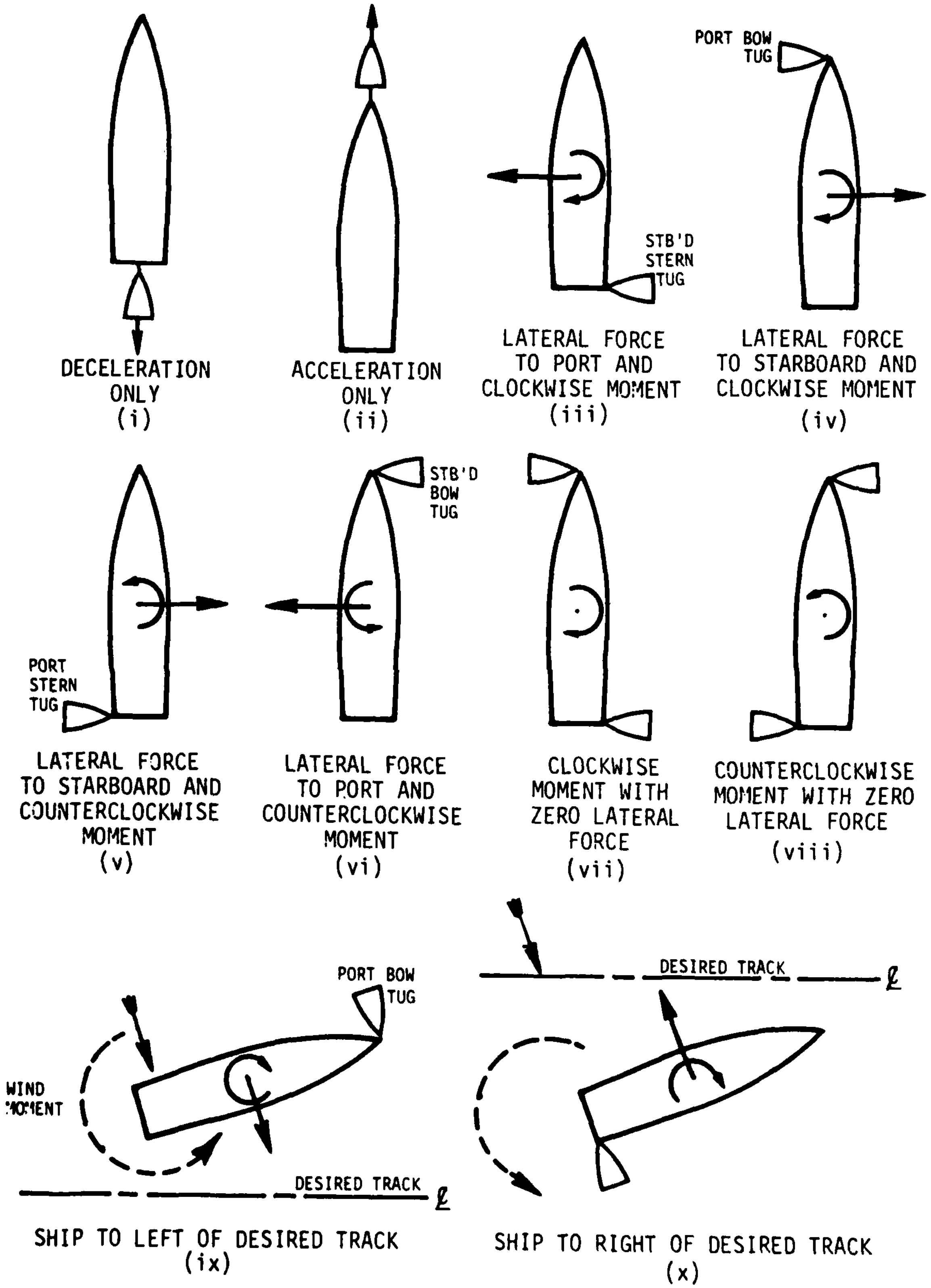


Figure 3-7. Simple Tug Strategies

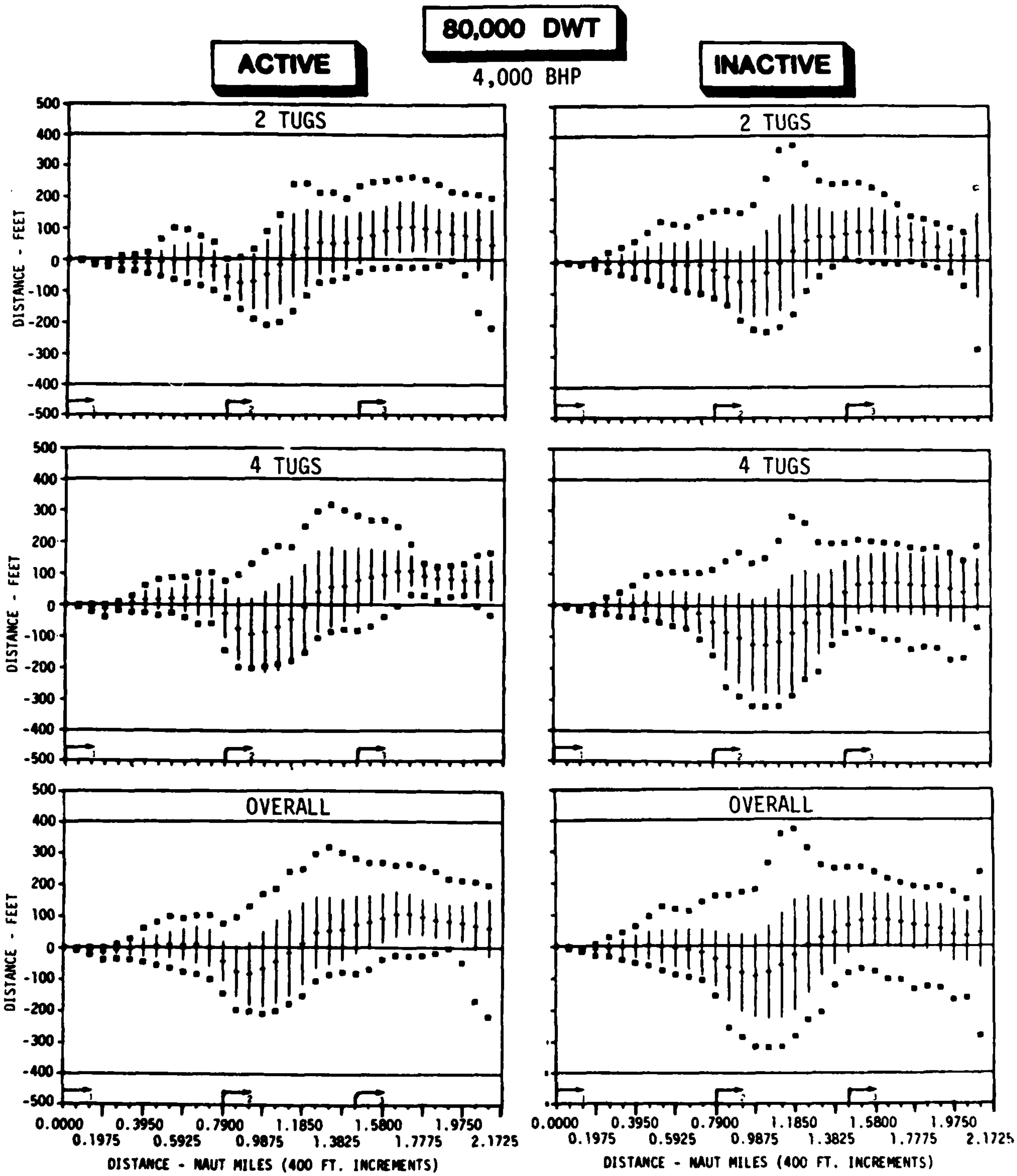


Figure 3-8A. Mean Track, Standard Deviation and Extremes at 400 Feet Intervals as a Function of Tug Number and Tug Mode (80,000 DWT Tanker, 4000 BHP)

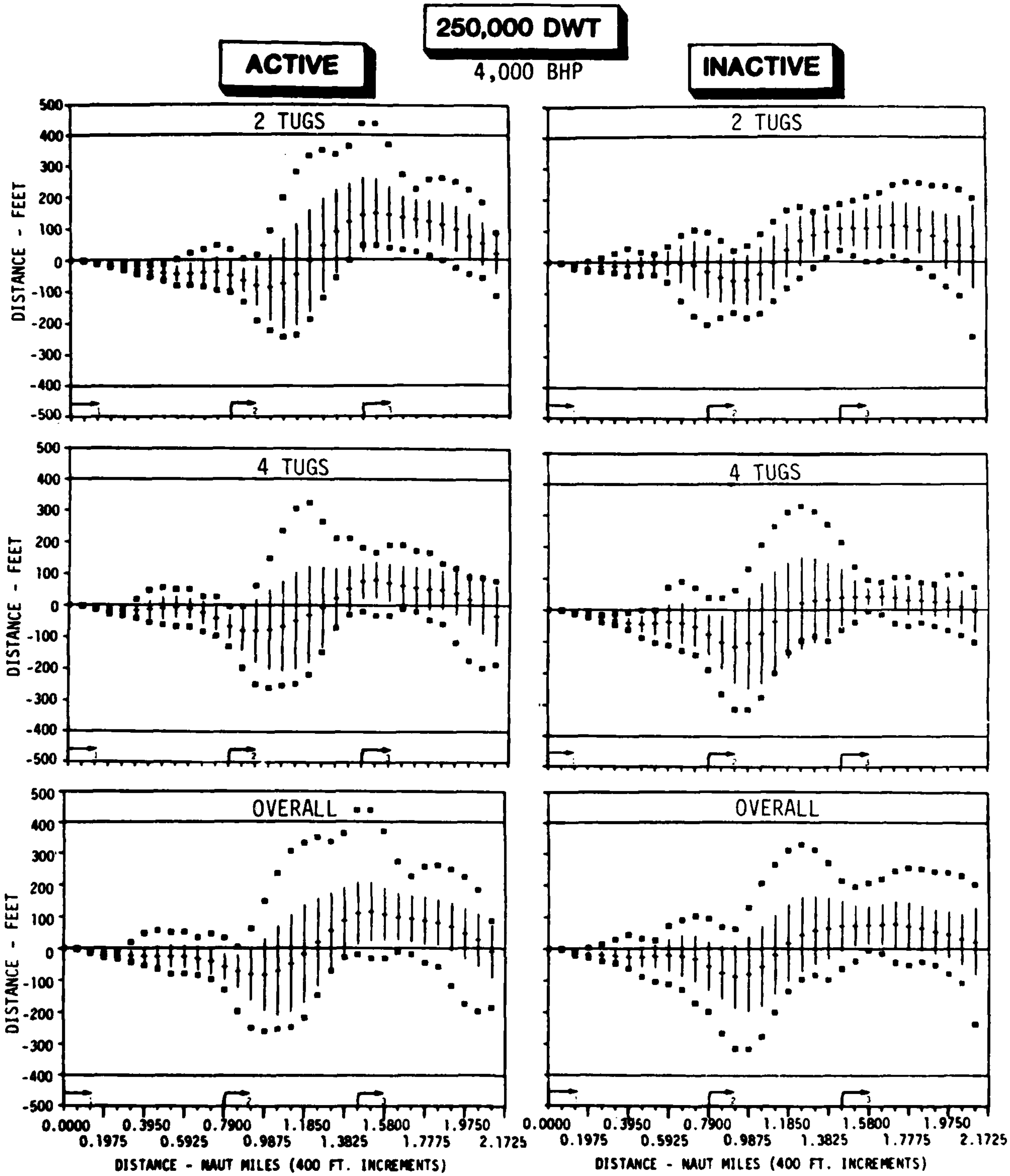


Figure 3-8B. Mean Track, Standard Deviation and Extremes at 400 Feet Intervals as a Function of Tug Number and Tug Mode (250,000 DWT Tanker, 4000 BHP)

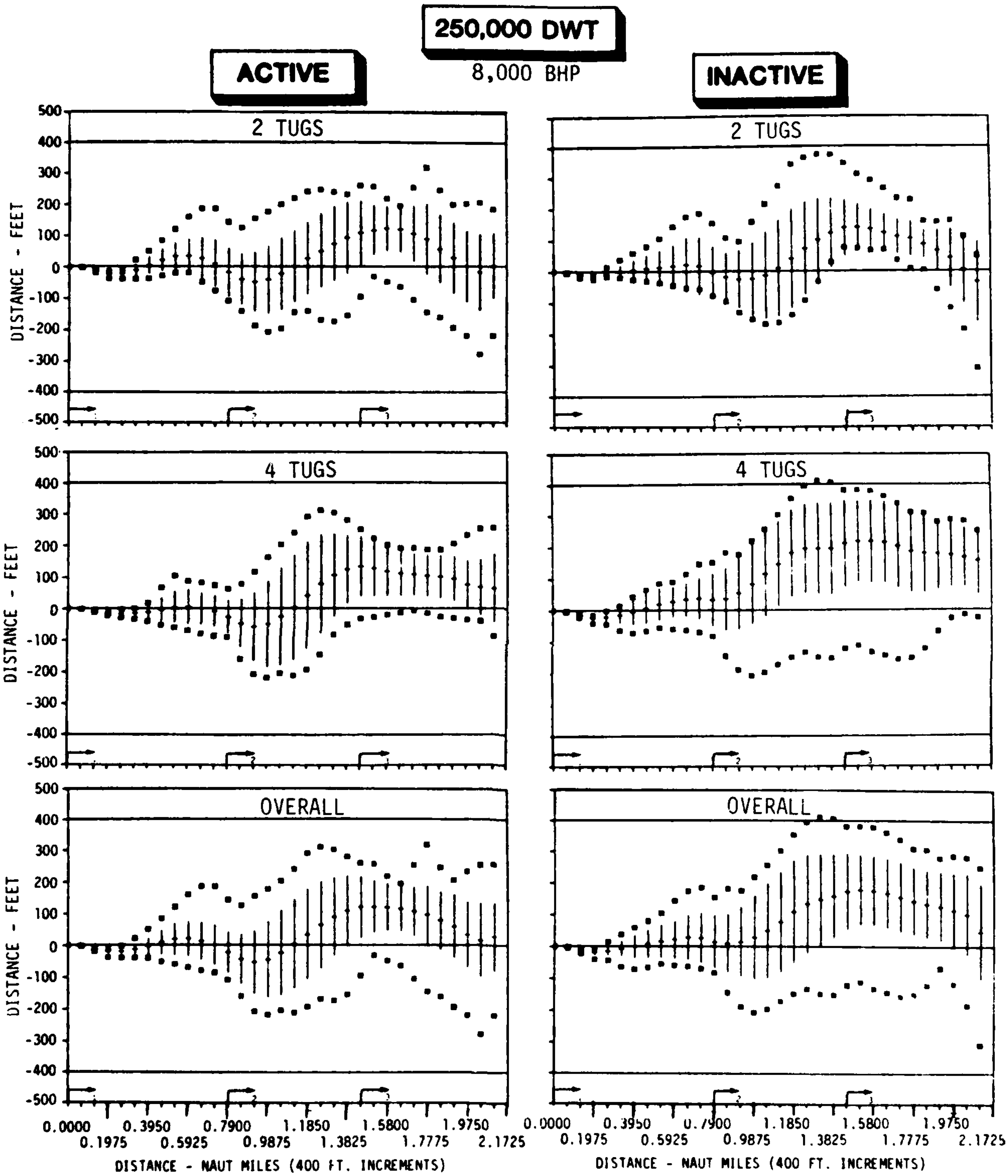


Figure 3-8C. Mean Track, Standard Deviation and Extremes at 400 Feet Intervals as a Function of Tug Number and Tug Mode (250,000 DWT Tanker, 8000 BHP)

CHAPTER 4

CONCLUSIONS

As a result of the qualitative and quantitative analyses of this experiment, the following significant conclusions have been drawn:

- o The track plots did not show any significant difference in the outcome of the shiphandling techniques employed by the harbor pilots and by the docking masters. Both groups demonstrated a wide variation in shiphandling techniques using conventional rudder and engine controls to maneuver in the first leg and the turn.

- o Even though the docking masters had tug support readily available, they did not find it necessary to use it, even with the larger ship, until entering the final deceleration stage.

- o This final deceleration stage, in the presence of the flood current and beam wind, proved to be most critical. Tug assistance was necessary, especially with the larger ship.

- o Even when the pilots of the 250,000 DWT tanker had 8000 HP available, under normal conditions and in the final deceleration phase, they still used about the same amount of RMS tug moment on the ship as they did when only 4000 HP was available. In their opinion, this amount was apparently sufficient for controlling the ship.

- o At the 4000 HP level, there was a significant increase in tug moment (in the final stages) when four tugs rather than two were used. At the higher level, much more tug moment was produced when using only two tugs.

- o The mean speed of the 250,000 DWT tanker was always higher than that of the 80,000 DWT ship in the first leg and in the turn but comparable in the third leg. This higher speed greatly reduced the influence of wind and current. With replicate runs, the speed of the larger ship did not change. The 80,000 DWT tanker, however, started slowly, experienced problems with wind and current, and in its next run increased speed. The speed did not change significantly in the third run. Due to its higher speed in the turn and also its higher inertia, the larger ship required considerable tug assistance in safely decelerating in the third leg.

- o The tug usage with the 80,000 DWT tanker was negligible throughout the transits, indicating that pilots were capable of handling this size ship without tugs under normal conditions.

- o Due to its higher speed, the inherent risk of grounding was always greater with the larger ship. As the 80K ship increased speed in its first two runs, it improved its deviation off track in the turn, reduced the amount of rudder angle it was using, but increased the danger of grounding should a failure occur.

- The results of a simple inherent risk analysis indicated that even under ideal conditions in this channel geometry a speed of three knots should not be exceeded in the turn. This would minimize the possibility of grounding in the event of a complete mechanical failure (assuming a five minute recovery time). At four knots, on the other hand, the risk would be close to 100 percent. This indicates that even small time lags and small speed differentials are critical to a successful passage. These calculations are well substantiated by the large number of groundings that actually did occur in the experiment following a failure at the beginning of the turn (leg 2).

- The inherent risk factor was highest in the turn, and smallest in the final leg. This is due to the ship speed and principally the limitations in dimensions of the waterway in the channel elbow.

- The experiment showed that when a complete mechanical failure occurred with the 250,000 DWT tanker, there were 13 groundings out of a total of 16 runs. Therefore, it would appear that 4000 HP was insufficient to prevent grounding of these large ships at the speeds they were using. With 8000 HP tug power available, there was a considerable improvement, but 8 groundings out of 16 runs still took place. The important factor appears to be the ship response time at these speeds.

- The occurrence of a complete failure presented great difficulty to the majority of the pilots in this scenario, particularly with the larger ship at the lower horsepower. Even those pilots who avoided grounding experienced considerable difficulty at various sections of the harbor during transit.

- There were large variations in the time lapse after failure before the pilots applied their tug power. This time lag is critical to minimizing the possibility of grounding. It corresponds to distance travelled by the ship in the limited maneuvering area of the first leg and the turn.

- Groundings with the 80,000 DWT tanker occurred principally in the final leg where the ship was very susceptible to wind and current. Tugs were able to help the ship complete the turn, but the occurrence of grounding appeared to be critically dependent on its closeness to the centerline and the angle of crossing the centerline as it enters the final leg.

- The 250,000 DWT tanker generally grounded in the turn. Because of its greater speed and its considerable inertia, it did not respond sufficiently to the tug forces at either power level and, consequently, in most cases failed to make the turn.

- The occurrence of grounding is clearly related to the condition of the ship at the time of failure (whether it has already initiated its turn, its speed, the tug power available, etc.) and, importantly, the pilot's time lag in applying his tugs, their subsequent use, and the ship response to these forces.

- There were indications of a dependence of mean speed of the 250,000 DWT tanker on tug mode and tug number, at the 8000 HP level, but not at the 4000 HP level.

- The swept path increased from leg 1 to leg 3, and in the final phase, there appeared to be a tug number and tug mode dependence.

- The deviation off-track did not change significantly between the two ships nor with tug mode. However, it apparently depended on whether two tugs or four tugs were being used. The largest values occurred in the turn. In the case of the smaller ship in its initial run a larger deviation occurred in the turn when the four tug configuration was used. For the 250,000 DWT tanker, however, the deviation was independent of tug number. It should be remembered that tugs were rarely used with both ships except in the final leg where the deviation off track tended to be reasonably constant.

- A greater amount of rudder was used by the larger ship despite its higher speed and, consequently, greater rudder effectiveness. This is indicative of the severity of the environmental effects due to ship size. The amount of rudder used increased from leg 1 to leg 3. In the final leg, although a large amount of rudder was being used, the rudder is very ineffective. During the time the engine is running in reverse to produce a rapid deceleration, it loses the turning capability of the rudder almost completely. With consecutive runs, the amount of rudder did not change on the 250,000 DWT ship. However, on the 80,000 DWT tanker, particularly in leg 2, the amount of rudder decreased with the second replicate run, due to the increase in speed in this ship with repetition.

  In the third leg, comparably large amounts of RMS rudder were used by both ships.

- A simultaneous rudder and engine failure without recovery has a very low probability of occurrence; yet, should it occur, the consequences could be serious in relatively confined waterways. The probability of the occurrence of an engine failure alone or a rudder failure alone, with or without recovery in a finite time is much greater.

  A further experiment will investigate the tug requirements and pilot behavior in these cases also.

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APPENDIX A

SAMPLE PILOT INSTRUCTIONS

The following instructions (Figure A-1) were presented, verbally and in printed form, to test subjects in Phase IA (tugs in attendance but inactive), Group 1 (80,000 DWT VLCC) using two tugs while wind blows from Northwest.

Instructions for Group 3 test subjects in Phase 2B (250,000 DWT tanker with two 4000 BHP tugs) follow (Figure A-2). Pilot Instructions were similarly altered as appropriate for each of the other experiment combinations (Table 2-1, Chapter 2).

PILOT INSTRUCTIONS

Group 1, Phase 1A (2 tugs)

You will be responsible for piloting an 80,000 DWT VLCC, fully loaded into a hypothetical harbor shown in the accompanying chart. The following are the pertinent characteristics of your ship.

Length	763 feet
Beam	125 feet
Draft	40 feet
Ahead HP	24,000
Propeller diameter	25 feet
Max. rudder angle	$\pm 35^{o}$
Rudder area	517.5 ft^2

A channel 800 ft. wide runs from the entrance (midway between buoys 3 and 4) due North until buoy 8 is reached, a distance of 3/4 n mile. The channel changes direction by 45^{o} and the inner portion of the turn is cut off until buoy 8A is reached. Beyond this point the channel centerline is in the northeasterly direction, 45^{o}. On emerging from the turn at station 8A a further 3/4 n mile must be travelled before reaching buoys 11 and 12. The ship speed is 7 knots through the water at the entrance point, and there is a 1 knot flood (following) current directed along the channel centerline and curving appropriately at the bend. A wind of 30 knot average strength and gusting $\pm$ 10 knots around this average value blows from the Northwest (315^{o}) on the average, but fluctuates $\pm 30^{o}$ around this average direction.

The depth of the water in the channel is 46' giving a 6 ft. underkeel clearance, and depth/draft ratio of 1:15. Outside the channel the

Figure A-1. Pilot Instructions, Group 1, Phase 1A (2 Tugs)

water depth is 15 feet. You will experience hydrodynamic interactions between your ship and the channel bottom and boundaries in the simulator. However, changes in trim and squat will not be observed.

You will commence your transit at the midpoint between buoys 3 and 4 as indicated. Your speed through the water will be seven knots, with the 1 knot following current. You will experience the 30 knot gusting wind from the NW as described above. Two tugs, each 2,000 HP, which are highly maneuverable, and more powerful versions of the Wilmington Launch Tug "Tina," will be available at the entrance and will hook up with your ship in the attendance mode. The tugs will be placed in positions to be designated by you. A period of five minutes will pass before these tugs can become effective. Thereafter, a period of two minutes will be required to move a tug from one side of the ship to the other, and a time of one minute will expire before your command can be effected by a tug once its position is fixed. These tugs can contribute maximum thrusts of 54,000 lb. on a continuous basis at any heading and for speeds less than six knots. Full thrust can be generated aft and broadside as well as forward. The basic characteristics of the "Tina" type tug are:

> Length 65 ft., beam 26 ft. draft 10.5 ft.,
> Displacement tonnage 127.5, BHP 1,000.

The propulsion comprises two diesel engines coupled to 360° steerable propulsion units with propellers in Kort nozzles. The two propellers are mounted aft, and the tugboat can operate as a tractor tug when going astern. The propellers are right-handed, four bladed type, of 5.33 ft. diameter enclosed in a Kort nozzle.

The accompanying figure shows the position of the attachment points available, and also the convention to be used in giving tug orders. For example, starboard bow full ahead corresponds to a 54,000 lb. push against the bow attachment point, at 270° to the ship centerline. Starboard bow full reverse corresponds to a 54,000 lb. pull at 90° to the centerline. The tug orders for thrust, in forward and reverse, are full, half, slow, dead slow and stop corresponding to forces of 54,000, 27,000, 13,500, 5,400 and zero lb.

The attachment points are located forward and aft of the center of gravity at one third ship length, i.e. $\pm$ 254 feet for your ship, at midship in line with the center of gravity, and at the stem and stern ($\pm$ 380 feet respectively).

Experiment Procedure

Prior to the main experiment, you will be allowed to perform a familiarization run by transiting the channel from beginning to end in the

Figure A-1. Pilot Instructions, Group 1, Phase 1A (2 Tugs) (Continued)

80,000 DWT tanker. This will provide you with the opportunity to become familiar with the characteristics of the ship and the scenario. During this run wind, current and tugs will not be present. At all times, during this and subsequent runs, we expect that in your participation at CAORF you will act at all times as you would normally on board a real ship. Therefore, you should treat this simple exercise as though it were a real world transit, and follow a course comparable to one you would normally follow in a similar situation.

You will then undertake four transits of the channel under the external environmental forces of wind and current, and with tugs now available subject to the constraints described previously. These 2 tugs will be inactive and in attendance and should only be used in the case of an extreme emergency such as an engine or rudder failure or a combination of both. You will enter the channel at seven knots and attempt to reduce your speed to zero speed over the ground when you reach the location midway between buoys 11 and 12. This you will accomplish by manipulating the rudder and the engine rpm in the best manner for a safe transit. By repeating the experiment, you will have the opportunity to improve your technique, if necessary.

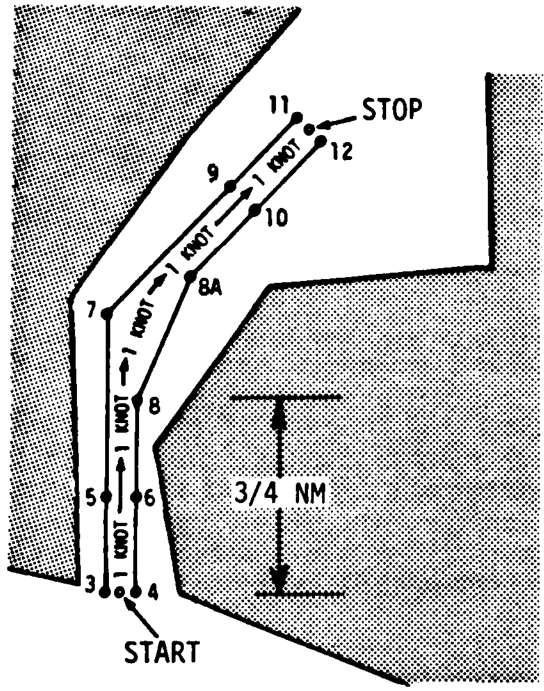
If the environmental conditions used in the experiment appear to be over severe, it should be understood that the values were selected with the experimental objective in mind.

Engine orders should be given in the telegraph mode (Full Ahead 60 rpm, Half Ahead 40 rpm, Slow Ahead 20 rpm, Dead Slow 10 rpm). A mate on watch will relay your engine commands and record bell book entries.

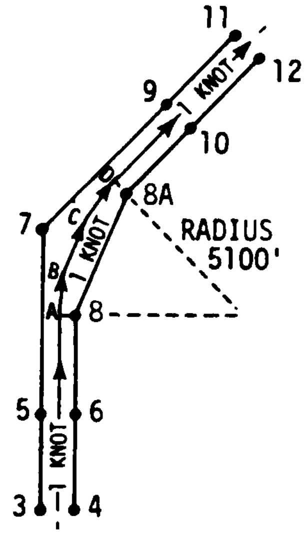
Since you will not have the capability in the simulator to observe the placement of your tugs, we are providing a closed circuit TV monitor in the wheelhouse. The display will indicate the positions and directions of the active tug thrusts (but not their magnitude) by arrows. Where a tug is in attendance, but inactive, it is represented by a square placed in the last active position of the tug. The arrows will be moved and placed in position at the instant your command is answered by the tug.

Figure A-1. Pilot Instructions, Group 1, Phase 1A (2 Tugs) (Continued)

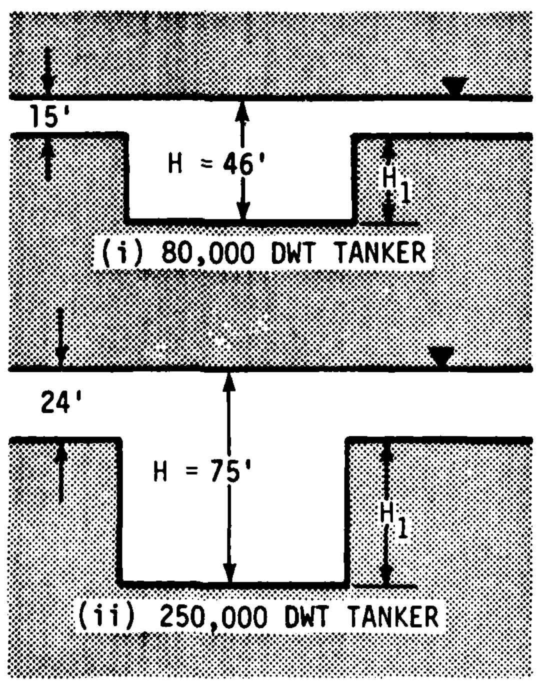
Harbor Information Supplied to Subjects (Reduced Scale)



HARBOR CONFIGURATION



CURRENT IN TURN



CHANNEL CROSS SECTIONS

Figure A-1. Pilot Instructions, Group 1, Phase 1A (2 Tugs) (Continued)

Tug Information Supplied to Subjects (Reduced Scale)

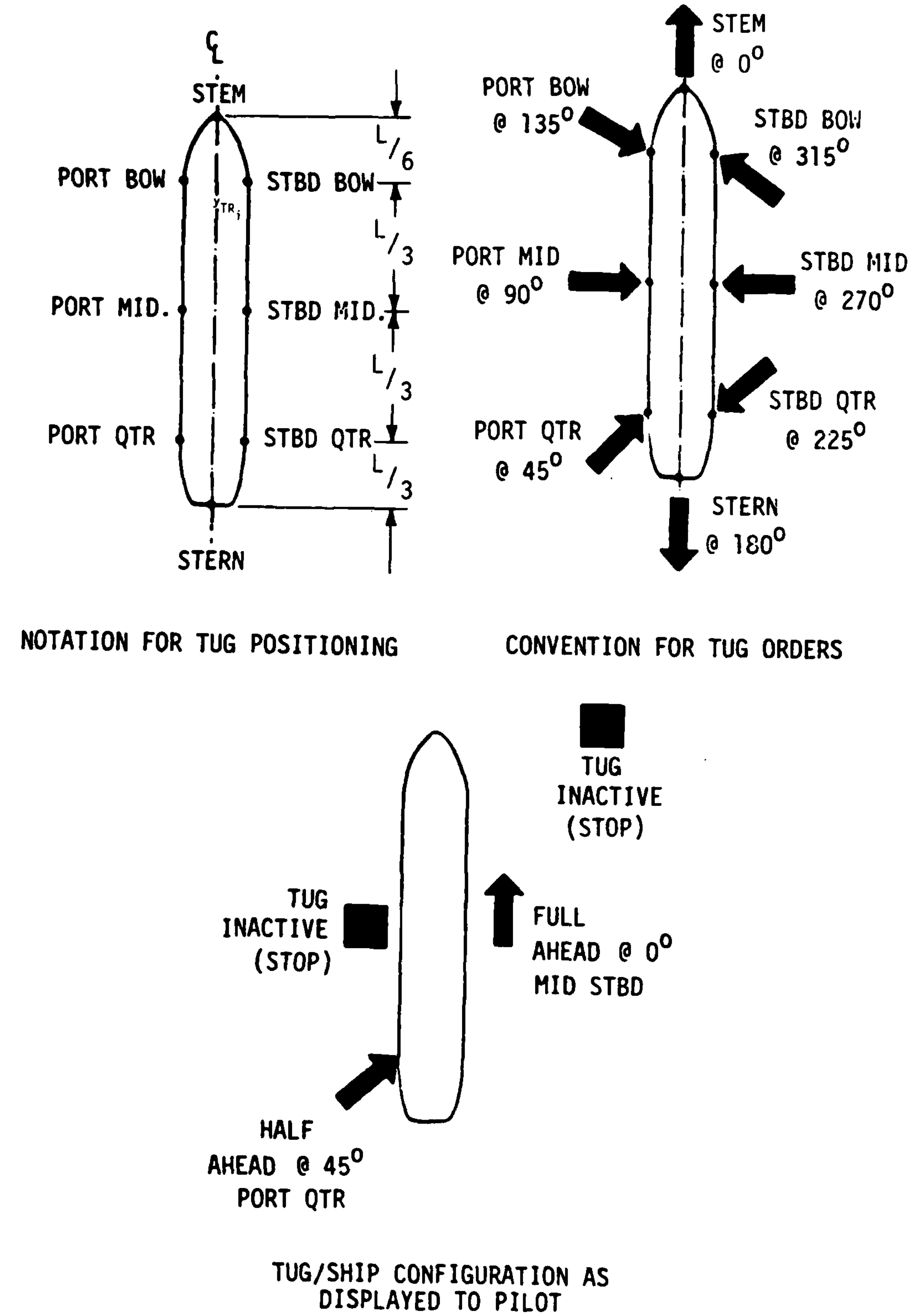


Figure A-1. Pilot Instructions, Group 1, Phase 1A (2 Tugs) (Continued)

PILOT INSTRUCTIONS

Group 3, Phase 2B (2 tugs)

You will be responsible for piloting a 250,000 DWT VLCC, fully loaded into a hypothetical harbor shown in the accompanying chart. The following are the pertinent characteristics of your ship.

Length	1,085 feet
Beam	170 feet
Draft	65 feet
Ahead HP	36,000
Propeller diameter	29.2'
Max. rudder angle	$\pm$ 35^{o}
Rudder area	1,302 ft.^{2}

A channel 800 ft. wide runs from the entrance (midway between buoys 3 and 4) due North until buoy 8 is reached, a distance of 3/4 n mile. The channel changes direction by 45^{o} and the inner portion of the turn is cut off until buoy 8A is reached. Beyond this point the channel centerline is in the northeasterly direction, 45^{o}. On emerging from the turn at station 8A a further 3/4 n mile must be travelled before reaching buoys 11 and 12. The ship speed is 7 knots through the water at the entrance point, and there is a 1 knot flood (following) current directed along the channel centerline and curving appropriately at the bend. A wind of 30 knot average strength and gusting $\pm$ 10 knots around this average value blows from the Northwest (315^{o}) on the average, but fluctuates $\pm$ 30^{o} around this average direction.

The depth of the water in the channel is 75' giving a 10 ft. under-keel clearance, and a depth/draft ratio of 1:15. Outside the channel the water depth is 24 feet. You will experience hydrodynamic interactions between your ship and the channel bottom and boundaries in the simulator. However, changes in trim and squat will not be observed.

You will commence your transit at the midpoint between buoys 3 and 4 as indicated. Your speed through the water will be seven knots, with the 1 knot following current. You will experience the 30 knot gusting wind from the NW as described above. Two tugs, each 4,000 HP, which are highly maneuverable, and more powerful versions of the Wilmington Launch Tug "Tina," will be available at the entrance and will hook up with your ship in the attendance mode. The tugs will be placed in positions to be designated by you. A period of five minutes will pass before these tugs can become effective. Thereafter, a period of two minutes will be required to move a tugs from one side of the ship to the other, and a time of one minute will expire before you command can be effected by a tug once its position is fixed. These tugs can contribute maximum thrusts of 54,000 lb. on a continuous basis at any

Figure A-2. Pilot Instructions, Group 3, Phase 2B (2 Tugs)

heading and for speeds less than six knots. Full thrust can be generated aft and broadside as well as forward. The basic characteristics of the "Tina" type tug are:

Length 65 ft., beam 26 ft., draft 10.5 ft.,
Displacement tonnage 127.5, BHP 1,000

The propulsion comprises two diesel engines coupled to 360° steerable propulsion units with propellers in Kort nozzles. The two propellers are mounted aft, and the tugboat can operate as a tractor tug when going astern. The propellers are right-handed, four bladed type, of 5.33 ft. diameter enclosed in a Kort nozzle.

The accompanying figure shows the position of the attachment points available, and also the convention to be used in giving tug orders. For example, starboard bow full ahead corresponds to a 108,000 lb. push against the bow attachment point, at 270° to the ship centerline. Starboard bow full reverse corresponds to a 108,000 lb. pull at 90° to the centerline. The tug orders for thrust, in forward and reverse, are full, half, slow, dead slow and stop corresponding to forces of 108,000, 54,000, 27,000, 10,8000 and zero lb.

The attachment points are located forward and aft of the center of gravity at one third ship length, i.e., ± 360 feet for your ship, at midship in line with the center of gravity, and at the stem and stern (± 540 feet respectively).

Experiment Procedure

Prior to the main experiment, you will be allowed to perform a familiarization run by transiting the channel from beginning to end in the 250,000 DWT tanker. This will provide you with the opportunity to become familiar with the characteristics of the ship and the scenario. During this run wind, current and tugs will not be present. At all time, during this and subsequent runs, we expect that in you participation at CAORF you will act at all times as you would normally on board a real ship. Therefore, you should treat this simple exercise as though it were a real world transit, and follow a course comparable to one you would normally follow in a similar situation.

You will then undertake four transits of the channel under the external environmental forces of wind and current, and with tugs now available subject to the constraints described previously. You will enter the channel at seven knots and attempt to reduce your speed to zero speed over the ground when you reach the location midway between buoys 11 and 12. This you will accomplish by manipulating the rudder, the engine rpm, and the available tug power, in the best manner for a safe transit. By repeating the experiment, you will have the opportunity to improve your technique, if necessary.

Figure A-2. Pilot Instructions, Group 3, Phase 2B (2 Tugs) (Continued)

If the environmental conditions used in the experiment appear to be over severe, it should be understood that the values were selected with the experiment objective in mind.

Engine order should be given in the telegraph mode (Full Ahead 60 rpm, Half Ahead 40 rpm, Slow Ahead 20 rpm, Dead Slow 10 rpm). A mate on watch will relay your engine commands and record bell book entries.

Since you will not have the capability in the simulator to observe the placement of your tugs, we are providing a closed circuit TV monitor in the wheelhouse. The display will indicate the positions and directions of the active tug thrusts (but not their magnitude) by arrows. Where a tug is in attendance, but inactive, it is represented by a square placed in the last active position of that tug. The arrows will be moved and placed in position at the instant your command is answered by the tug.

Figure A-2. Pilot Instructions, Group 3, Phase 2B (2 Tugs) (Continued)

APPENDIX B

TUG ASSISTANCE FOLLOWING FAILURE

In the derivation of the "inherent risk" factor, α, (Section 2-11) three recovery times were considered and in the estimation of α the effect of the tugs on the ship's trajectory after failure was neglected. The following simple analyses were performed to assess the magnitude of this assumption.

Suppose a ship is travelling due North in a narrow waterway with a speed u_o but with no yaw rate, side drift, etc. and in the absence of wind and current. At this point a complete failure takes place and tugs in attendance are called upon to exert control and prevent subsequent grounding. If the tug assistance were not considered and the ship continued at a constant speed thereafter (assuming hull drag to be negligible) it would advance a distance S in a time t_o where $S = u_o t_o$. This was the underlying assumption in the risk calculation.

Now, if the tugs can provide assistance instantaneously the subsequent ship's track (advance and transfer) can be estimated.

It is assumed that the tugs can be deployed in the following configurations:

a) A tug at the stem exerting a yawing moment on the ship, while the second tug, pulling at the stern, produces a deceleration. Both tugs are working at full power and therefore giving their maximum forces.

b) Both tugs are deployed to pull at the stern to produce maximum deceleration. Again, both are operating at full power and producing maximum forces.

The solution in case (a) require the application of an off-line ship-tug dynamics program that has been developed at CAORF, whereas case (b) can be solved readily. In this case the distance advanced (S) in time t_o is simply

$$S = u_o t_o - 1/2 \left(\frac{F}{m_{eff}}\right) t_o^2$$

where (F/m_{eff}) is the constant deceleration produced by the tug force F, and m_{eff} is the effective mass of the ship. This effective mass depends on the relative values of water depth and ship draft. A value of 1.10 is assumed here. The force F exerted by the two tugs is calculated from the total available horsepower (P) and a maximum bollard pull of 27 pounds per horsepower, i.e., F = 27 P.

The following calculations were performed for the 250,000 DWT tanker ($m_{eff} = 19.25 \times 10^6$ slugs) travelling at 4.5 knots when failure occurs. A reasonable mean speed (based on the experiment data) at which failures occur is 4.5 knots. Two levels of total horsepower are available (as used in the experiment) namely, 4000 and 8000 BHP.

Configuration (b) - 8000 BHP

8000 BHP produces a maximum pull of 216,000 lb. The constant deceleration produced by this force on the 19.25×10^6 slug mass = 0.01122 feet/sec^2. The advances calculated for the three time periods selected (t_o = 2-1/2, 5 and 10 minutes) were 1014, 1776 and 2544 feet respectively. After 11.3 minutes the ship will be completely stopped and its advance at that time will be 2544 feet.

Configuration (b) - 4000 BHP

With only half the previous tug horsepower available the maximum deceleration will also be halved, namely .00561 $feet/sec^2$. The advances calculated for the three selected times will now become 1077, 2028 and 3552 feet respectively.

Constant Speed Case

Without tug assistance the advance is simply $S = u_o t_o = 7.6 t_o$ or 1140, 2280 and 4560 feet for the same three times.

Configuration (a) - 8000 BHP

The ship-tug dynamics program was exercised to derive the advance and transfer for the 250,000 DWT tanker when two tugs were in attendance with a total of 8000 BHP available. The results indicated that there was again a constant deceleration along the curved track (0.00676 $feet/sec^2$ -- about 20% higher than would be produced by a stern tug alone, due to the hydrodynamic drag produced in turning). The results of this analysis are presented along with the results of the other analyses in Table B-1 and in Figure B-1.

An examination of the data in Table B-1 and Figure B-1 shows clearly that the tug influence on the ship's advance following a failure is negligible during the first few minutes and small eve.. during the first five minutes. It is not until a period of up to ten minutes has elapsed that an appreciable difference in advances calculated under the different conditions is apparent. In addition, when one considers that, in practice, finite time lags actually occur before tugs become effective, it appears reasonable to neglect the tug influence following the failure for times up to ten minutes as has been done here in calculating the risk factor α.

As pointed out previously the use of the tugs prior to the failure effects the ship's state variables at the time of failure, and in this way effects the subsequent α calculation.

TABLE B-1. ADVANCE AND TRANSFER FOLLOWING FAILURE

250,000 DWT tanker, initial speed 4.5 knots with 4000 and 8000 total tug power available.

	Configuration (a)		Configuration (b)		
Time	Advance	Transfer	Advance	Transfer	Constant Speed
2.5	1052	0	1014 (1077)	--	1140
5.0	1952	200	1776 (2028)	--	2280
10.0	3245	900	2544 (3552)	--	4560

Values in brackets refer to 4000 BHP, the others to the 8000 BHP conditions.

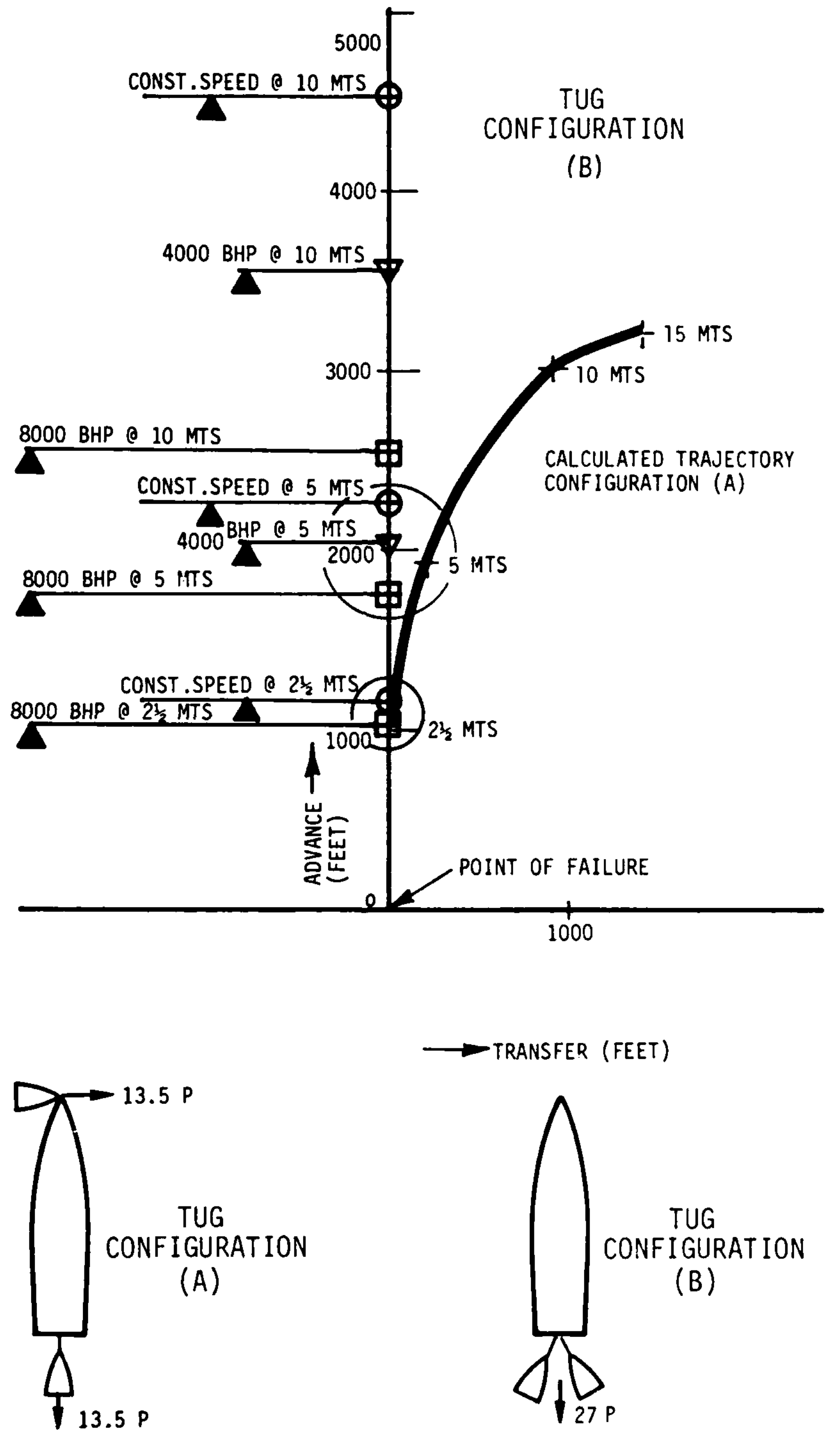


Figure B-1. Tug Assistance Following Failure

APPENDIX C

SIMPLE INHERENT RISK CALCULATION

The geometry of the turn is shown in Figure C-1. The radius (R) of the transition arc is 5100 feet, and the half channel width of the legs on either side of the turn is 400 feet. The ship is assumed to be perfectly on track and at some point, Q, defined by the angular coordinate θ, a complete failure takes place. The ship continues to move along the tangent to the arc QP with constant speed (U) and intersects the outer channel boundary at point P, where distance travelled, $S_0 = QP$. The lateral velocity of the stem or the stern is small

$$\left|\frac{v}{u}\right| = \frac{L}{2R} = \frac{1}{10}$$

and can be safely neglected in this calculation. Simple geometrical considerations show that the distance can be represented by

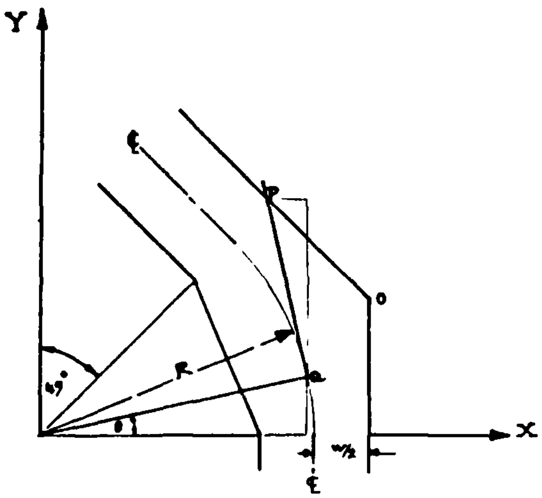


Figure C-1. Geometry for Risk Calculation

$$S_0 (\cos\theta - \sin\theta) = -R(\sin\theta + \cos\theta) + \left(R + \frac{W}{2}\right)(1 + \tan 22\text{-}1/2^\circ)$$

or

$$S_0 (\cos\theta - \sin\theta) = -5100(\sin\theta + \cos\theta) + 7778$$

The distance moved by the CG of the ship before its stem crosses the channel boundary is $S_G = (S_0 - L/2)$. The following Table of values of distance to grounding against ship position (θ) at failure was derived.

TABLE C-1. SHIP SPEED FOR NO GROUNDINGS

θ	S (feet)	Max. Ship Speed For No Grounding (kts)
0	2138	4.22
10	1762	3.48
15	1624	3.20
20	1534	3.03
22-1/2	1516	2.99
30	1676	3.31
35	2211	4.36
40	4275	8.43
45	infinite	--

On the assumption that recovery can take place in a period of five minutes (as discussed in Appendix B) a maximum value of ship speed at each position on the transition arc was also obtained, above which the local inherent risk of grounding was unity. The most critical point corresponds to halfway around the arc (θ = 22-1/2°)

and indicates that a speed of three knots or less would be necessary for no inherent risk, that is $\alpha_2 = 0$ for leg 2. If the speed were four knots or over this inherent risk would be high throughout the turn and α_2 would closely approach unity. This shows that the small margin of one knot could be critical should a complete failure take place.

APPENDIX D

STATISTICAL MAIN EFFECTS AND INTERACTIONS

This Appendix presents tables showing the main effects and interactions that were found to be significant for the performance measures treated in the experiment. These tables were utilized in the discussions presented in Chapter 3.

TABLE D-1. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) ANOVA 1

Parameter	80K (A1)	250K (A2)	Main Effect p Value
J1	1.45478	1.71741	ns
J2	1.75457	2.16907	0.05
J3	2.11821	2.39898	ns
α_1	0.01749	0.06118	ns
α_2	0.31727	0.51283	0.001
α_3	0.68092	0.74276	0.01
Distance Off Track Contribution	1.14893	1.18978	ns
Rudder Contribution	0.28350	0.42051	0.01
Tug Moment Contribution	0.00486	0.04594	0.001
Percentage Time Left Rudder	6.222	11.075	0.001
Percentage Time Right Rudder	63.587	58.510	ns
Time Rudder Used in Leg (min.)	9.49332	8.45718	ns
Swept Path (ft)	179.20013	245.91028	0.001
Mean Speed (ft/sec.)	5.80155	6.63283	0.01

TABLE D-2. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) ANOVA 1

Parameter	2 Tugs (B1)	4 Tugs (B2)	Main Effect p Value
J1	1.29033	1.88185	0.01
J2	1.69042	2.23322	0.01
J3	1.94818	2.56902	0.01
α_1	0.04155	0.03712	ns
α_2	0.44164	0.38847	ns
α_3	0.69939	0.72429	ns
Distance Off Track Contribution	0.92485	1.41386	0.05
Rudder Contribution	0.30539	0.39862	0.05
Tug Moment Contribution	0.01854	0.03226	0.01
Percentage Time Left Rudder	7.734	9.563	ns
Percentage Time Right Rudder	61.538	60.559	ns
Time Rudder Used in Leg (min.)	8.66646	9.28405	ns
Swept Path (ft)	205.61154	219.49893	0.01
Mean Speed (ft/sec.)	6.45095	5.98342	ns

TABLE D-3. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) ANOVA 1

Parameter	Inactive (C_1)	Active (C_2)	Main Effect p Value
J1	1.67756	1.49463	ns
J2	2.03280	1.89083	ns
J3	2.34346	2.17375	ns
α_1	0.04119	0.03747	ns
α_2	0.39644	0.43367	ns
α_3	0.70710	0.71659	ns
Distance Off Track Contribution	1.24819	1.09052	ns
Rudder Contribution	0.38488	0.31914	ns
Tug Moment Contribution	0.00392*	0.04751	0.001
Percentage Time Left Rudder	9.315	7.982	ns
Percentage Time Right Rudder	63.087	59.010	ns
Time Rudder Used in Leg (min.)	9.33994	8.61005	ns
Swept Path (ft)	212.30913	212.80128	ns
Mean Speed (ft/sec.)	6.20549	6.22888	ns

* This value should be exactly zero

TABLE D-4. RELATIONSHIP AMONG MEANS FOR RUN (D) 2, 3 and 4 - ANOVA 1

Parameter	Runs (D) 2	3	4	Main Effect p Value	Comparison (D) 2-3	2-4	3-4
J1	1.81335	1.55628	1.38866	0.05	ns	*	ns
J2	2.15029	1.93473	1.80043	ns	—	—	—
J3	2.48796	2.2152	2.07265	0.05	ns	*	ns
α_1	0.03276	0.04323	0.04202	ns	—	--	--
α_2	0.3697	0.42167	0.45379	0.05	ns	**	ns
α_3	0.70737	0.70214	0.72601	ns	—	—	—
Distance Off Track Contribution	1.34846	1.14140	1.01820	ns	—	—	—
Rudder Contribution	0.4076	0.3441	0.30432	0.001	**	**	ns
Tug Moment Contribution	0.02453	0.02756	0.02412	ns	—	—	—
Percentage Time Left Rudder	9.170	8.472	8.303	ns	—	—	—
Percentage Time Right Rudder	62.825	61.886	58.435	0.05	*	*	ns
Time Rudder Used in Leg (min.)	9.89283	8.94177	8.09115	0.001	*	**	ns
Swept Path (ft)	219.15344	211.26541	207.24695	0.01	*	**	ns
Mean Speed (ft/sec.)	5.83118	6.30604	6.51434	0.001	**	**	ns

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-5. RELATIONSHIP AMONG MEANS FOR LEGS (E) 1, 2 and 3 - ANOVA 1

Parameter	Leg (E) 2	Leg (E) 3	Leg (E) 4	Main Effect p Value	Comparison (E) 2-3	Comparison (E) 2-4	Comparison (E) 3-4
J1	0.38290	3.00302	1.37237	0.001	**	**	**
J2	0.81135	3.63126	1.44281	0.001	**	*	**
J3	1.37177	3.79481	1.60922	0.001	**	ns	**
α_1	0.00394	0.10999	0.00408	0.001	**	ns	**
α_2	0.43239	0.73825	0.07452	0 001	**	**	**
α_3	0.99281	0.90178	0.24092	0.001	**	**	**
Distance Off Track Contribution	0.18116	2.54073	0.78617	0.001	**	*	**
Rudder Contribution	0.19573	0.33677	0.52352	0.001	**	**	**
Tug Moment Contribution	0.00207	0.01553	0.0586	0.001	ns	**	**
Percentage Time Left Rudder	5.037	13.505	7.403	0.001	**	ns	**
Percentage Time Right Rudder	63.941	57.709	61.496	ns	—	—	—
Time Rudder Used in Leg (min.)	6.87851	8.39972	11.64753	0.001	**	**	**
Swept Path (ft)	180.27615	221.76257	235.62708	0.001	**	**	**
Mean Speed (ft/sec.)	8.33801	6.14225	4.17130	0.001	**	**	**

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-6. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY LEG (E) FOR J1
ANOVA I

Tug Number (B)	Leg (E) 1	2	3	Interaction p Value	Comparison (E) 2-3	2-4	3-4
2 Tugs	0.32297	2.27405	1.27399	0.01	**	**	**
4 Tugs	0.44282	3.73199	1.47076		**	**	**
Comparison (B)	ns	**	ns				

** p < 0.01
* p < 0.05
ns = not significant

TABLE D-7. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY RUN (D) BY LEG (E) FOR J1 ANOVA 1

Parameter		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
Inactive (C1)	Run (D) 2	0.45552	4.14025	1.67438	0.01	**	**	**
	3	0.44168	2.96889	1.24611		**	ns	**
	4	0.41945	2.37827	1.37347		**	*	**
Comparison (D)	2-3	ns	**	ns				
	2-4	ns	**	ns				
	3-4	ns	ns	ns				
Active (C2)	Run (D) 2	0.34039	2.75034	1.51921		**	**	**
	3	0.36121	3.06193	1.25786		**	*	**
	4	0.27911	2.71843	1.16321		**	*	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (C)	Run (D) 2	ns	**	ns				
	3	ns	ns	ns				
	4	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-8. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY LEG (E) FOR J2

ANOVA 1

	Leg (E)			Interaction	Comparison (E)		
Tug Number (B)	1	2	3	p Value	2-3	2-4	3-4
2 Tugs	0.78231	2.95665	1.33230	0.01	**	ns	**
4 Tugs	0.84039	4.30592	1.55332		**	ns	**
Comparison (B)	ns	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-9. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY RUN (D) BY LEG (E) FOR J2
ANOVA 1

Tug Mode (C)		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
Inactive (C1)	Run (D) 2	0.79341	4.65237	1.72964	0.05	**	*	**
	3	0.87965	3.59333	1.29383		**	ns	**
	4	0.86568	3.02535	1.46193		**	ns	**
Comparison (D)	2-3	ns	**	ns				
	2-4	ns	**	ns				
	3-4	ns	ns	ns				
Active (C2)	Run (D) 2	0.77943	3.33789	1.60900		**	ns	**
	3	0.78246	3.74186	1.31723		**	ns	**
	4	0.76747	3.43689	1.24525		**	ns	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (C)	2	ns	**	ns				
	3	ns	ns	ns				
	4	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-10. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUN (D) FOR J3

ANOVA 1

Ship Type (A)	Run Number (D) 2	3	4	Interaction p Value	Comparison (D) 2-3	2-4	3-4
80,000 DWT	2.59225	1.99119	1.77122	0.05	*	**	ns
250,000 DWT	2.38367	2.43921	2.37409		ns	ns	ns
Comparison (A)	ns	ns	*				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-11. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY LEG (E) FOR J3

ANOVA 1

Tugs Number (B)	Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
2 Tugs	1.32259	3.06005	1.46190	0.01	**	ns	**
4 Tugs	1.42096	4.52959	1.75674		**	ns	**
Comparison (B)	ns	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-12. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEGS (E) FOR α_1
ANOVA 1

Ship Type (A)	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
80,000 DWT	0.00000	0.05001	0.00246	0.05	ns	ns	ns
250,000 DWT	0.00787	0.16997	0.00570		**	ns	**
Comparison (A)	ns	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-13. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) BY TUG NUMBER (B) FOR α_1

ANOVA 1

80,000 DWT (A1) Inactive (C2)		Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
2 Tugs (B1)	Run (D) 2	0	0	0	0.05	ns	ns	ns
	3	0	0.11981	0		*	ns	*
	4	0	0.22858	0		**	ns	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	**	ns				
	3-4	ns	ns	ns				
4 Tugs (B2)	Run (D) 2	0	0	0		ns	ns	ns
	3	0	0.03750	0		ns	ns	ns
	4	0	0.05230	0.00641		ns	ns	ns
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (B)	Run (D) 2	ns	ns	ns				
	3	ns	ns	ns				
	4	ns	**	ns				

** $p < 0.01$
 * $p < 0.05$
ns = not significant

TABLE D-14. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) BY TUG NUMBER (B) FOR α_1

ANOVA 1

80,000 DWT (A1) Active (C2)		Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
2 Tugs (B1)	Run (D) 2	0	0	0	0.05	ns	ns	ns
	3	0	0.02574	0.02308		ns	ns	ns
	4	0	0.00424	0		ns	ns	ns
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
4 Tugs (B2)	Run (D) 2	0	0	0		ns	ns	ns
	3	0	0.01027	0		ns	ns	ns
	4	0	0.01027	0		*	ns	*
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (B)	Run (D) 2	ns	ns	ns				
	3	ns	**	ns				
	4	ns	*	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-15. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) BY TUG NUMBER (B) FOR α_1
ANOVA 1

250,000 DWT (A2) Inactive (C1)		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
2 Tugs (B1)	Run (D) 2	0	0.11942	0	0.05	*	ns	*
	3	0	0.06481	0		ns	ns	ns
	4	0	0.07083	0.01016		ns	ns	ns
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
4 Tugs (B2)	Run (D) 2	0.05900	0.20370	0		*	ns	**
	3	0.02451	0.27838	0		**	ns	**
	4	0.00490	0.21078	0		**	ns	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (B)	Run (D) 2	ns	ns	ns				
	3	ns	ns	ns				
	4	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-16. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) BY TUG NUMBER (B) FOR α_1

ANOVA 1

250,000 DWT (A2) Active (C2)		Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
2 Tugs (B1)	Run (D) 2	0	0.15086	0	0.05	*	ns	*
	3	0	0.36897	0.04369		**	ns	**
	4	0.00455	0.24649	0.01453		**	ns	**
Comparison (D)	2-3	ns	**	ns				
	2-4	ns	ns	ns				
	3-4	ns	*	ns				
4 Tugs (B2)	Run (D) 2	0.00962	0.25168	0		**	ns	**
	3	0	0.04064	0		ns	ns	ns
	4	0	0.03302	0		ns	ns	ns
Comparison (D)	2-3	ns	**	ns				
	2-4	ns	**	ns				
	3-4	ns	ns	ns				
Comparison (B)	Run (D) 2	ns	ns	ns				
	3	ns	**	ns				
	4	ns	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-17. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) BY TUG NUMBER (B) FOR α_1 - SHIP COMPARISONS
ANOVA 1

Comparison (A)	Runs (D)	Legs (E) 1	2	3
2 Tugs Inactive (C1 B1)	2	ns	*	ns
	3	ns	*	ns
	4	ns	*	ns
2 Tugs Active (C1 B2)	2	ns	**	ns
	3	ns	**	ns
	4	ns	**	ns
4 Tugs Inactive (C2 B1)	2	ns	*	ns
	3	ns	**	ns
	4	ns	**	ns
4 Tugs Active (C2 B2)	2	ns	**	ns
	3	ns	ns	ns
	4	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-18. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) BY TUG NUMBER (B) FOR α_1 - TUG MODE COMPARISONS ANOVA 1

Comparison (C)	Runs (D)	Legs (E) 1	2	3
80K, 2 Tugs (A1 B1)	2	ns	ns	ns
	3	ns	ns	ns
	4	ns	**	ns
80K, 4 Tugs (A1 B2)	2	ns	ns	ns
	3	ns	ns	ns
	4	ns	ns	ns
250K, 2 Tugs (A2 B1)	2	ns	ns	ns
	3	ns	**	ns
	4	ns	**	ns
250K, 4 Tugs (A2 B2)	2	ns	ns	ns
	3	ns	**	ns
	4	ns	**	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-19. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUN (D) FOR α_2
ANOVA 1

	Run Number (D)			Interaction	Comparison (D)		
Ship Type (A)	2	3	4	p Value	2-3	2-4	3-4
80,000 DWT	0.22418	0.33483	0.39281	0.05	**	**	ns
250,000 DWT	0.51521	0.50851	0.51477		ns	ns	ns
Comparison (A)	**	**	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-20. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEGS (E) FOR α_2

ANOVA I

Ship Type (A)	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
80,000 DWT	0.27324	0.62397	0.05461	0.001	**	**	**
250,000 DWT	0.59154	0.85253	0.09443		**	**	**
Comparison (A)	**	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-21. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY LEG (E) FOR α_2

ANOVA 1

Tug Number (B)	Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
2 Tugs	0.45972	0.79925	0.06594	0.05	**	**	**
4 Tugs	0.40506	0.67725	0.08310		**	**	**
Comparison (B)	ns	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-22. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) FOR α_2

ANOVA I

		Leg (E)		Interaction	Comparison (E)			
		1	2	3	p Value	1-2	1-3	2-3
	Run (D) 2	0.39603	0.64054	0.07252	0.01	**	**	**
Runs (D)	3	0.43267	0.77045	0.06189		**	**	**
	4	0.46848	0.80376	0.03914		**	**	**
	2-3	ns	**	ns				
Comparison (D)	2-4	*	**	ns				
	3-4	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-23. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUN (D) BY LEG (E) FOR α_2 ANOVA 1

Ship Type (A)		Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
80,000 DWT	Run (D) 2	0.19034	0.42305	0.05915	0.01	**	**	**
	3	0.29102	0.67537	0.03811		**	**	**
	4	0.33838	0.77349	0.06656		**	**	**
Comparison (D)	2-3	*	**	ns				
	2-4	**	**	ns				
	3-4	ns	*	ns				
250,000 DWT	Run (D) 2	0.60172	0.85803	0.08589		**	**	**
	3	0.57432	0.86553	0.08567		**	**	**
	4	0.59858	0.83402	0.11172		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (A)	Run (D) 2	**	**	ns				
	3	**	**	ns				
	4	**	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-24. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY LEG (E) FOR α_3

ANOVA 1

Tug Number (B)	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
2 Tugs	1.00000	0.90265	0.19553	0.05	**	**	**
4 Tugs	0.98562	0.90092	0.28632		**	**	**
Comparison (B)	ns	ns	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-25. RELATIONSHIP AMONG MEANS FOR LEG (E) BY RUN (D) FOR α_3

ANOVA 1

		Leg (E)		Interaction		Comparison (E)		
		1	2	3	p Value	1-2	1-3	2-3
Run (D)	2	0.98625	0.86853	0.26732	0.05	**	**	**
	3	0.99219	0.91304	0.20120		**	**	**
	4	1.00000	0.92378	0.25426		**	**	**
	2-3	ns	ns	*				
Comparison (D)	2-4	ns	ns	ns				
	3-4	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-26. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUN (D) BY TUG NUMBER (B) FOR α_3

ANOVA 1

Ship Type (A)		Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
80,000 DWT	Run (D) 2	0.97250	0.79533	0.26406	0.05	**	**	**
	3	0.98438	0.87706	0.15485		**	**	**
	4	1.00000	0.90791	0.17222		**	**	**
Comparison (D)	2-3	ns	*	**				
	2-4	ns	**	ns				
	3-4	ns	ns	**				
250,000 DWT	Run (D) 2	1.00000	0.94173	0.27057		ns	**	**
	3	1.00000	0.94902	0.24755		ns	**	**
	4	1.00000	0.93966	0.33629		ns	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	*				
Comparison (A)	Run (D) 2	ns	**	ns				
	3	ns	*	**				
	4	ns	ns	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-27. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUN (D) FOR DISTANCE OFF TRACK CONTRIBUTION - ANOVA 1

Ship Type (A)	Run Number (D)			Interaction	Comparison (D)		
	2	3	4	p Value	2-3	2-4	3-4
80,000 DWT	1.54823	1.04969	0.84887	0.05	*	**	ns
250,000 DWT	1.14869	1.23312	1.18753		ns	ns	ns
Comparison (A)	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-28. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY LEG (E) FOR DISTANCE OFF TRACK - ANOVA 1

Tug Number (B)	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
2 Tugs	0.17503	1.87307	0.72645	0.01	**	ns	**
4 Tugs	0.18729	3.20840	0.84589		**	ns	**
Comparison (B)	ns	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-29. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY TUG NUMBER (B) BY RUN (D) FOR DISTANCE OFF TRACK - ANOVA 1

Ship Type (A)	Run (D) 2	3	4	Interaction p Value	Comparison (D) 2-3	2-4	3-4
80,000 DWT (A1)							
2 Tugs	0.94130	0.94555	0.80057	0.05	ns	ns	ns
4 Tugs	2.15515	1.15382	0.89718		**	**	ns
Comparison B	**	ns	ns				
250,000 DWT (B)							
2 Tugs	1.00649	0.94666	0.90851		ns	ns	ns
4 Tugs	1.29089	1.51957	1.46655		ns	ns	ns
Comparison B	ns	ns	ns				
Comparison A							
2 Tugs	ns	ns	ns				
4 Tugs	**	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-30. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUN (D) BY LEG (E) FOR DISTANCE OFF TRACK - ANOVA 1

Ship Type (A)		Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
80,000 DWT	Run (D) 2	0.14874	3.54409	0.95185	0.05	**	*	**
	3	0.21509	2.29108	0.64288		**	ns	**
	4	0.20648	1.87152	0.46861		**	ns	**
Comparison (D)	2-3	ns	**	ns				
	2-4	ns	**	ns				
	3-4	ns	ns	ns				
250,000 DWT	Run (D) 2	0.14755	2.33767	0.96086		**	*	**
	3	0.20923	2.82134	0.66878		**	ns	**
	4	0.15986	2.37870	1.02404		**	*	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (A)	Run (D) 2	ns	**	ns				
	3	ns	ns	ns				
	4	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-31. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY RUN (D) BY LEG (E) FOR DISTANCE OFF TRACK - ANOVA 1

Tug Mode (C)		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
Inactive (C1)	Run (D) 2	0.17208	3.64602	1.01644	0.05	**	*	**
	3	0.25031	2.47993	0.67728		**	ns	**
	4	0.24756	1.89285	0.85127		**	ns	**
Comparison (D)	2-3	ns	**	ns				
	2-4	ns	**	ns				
	3-4	ns	ns	ns				
Active (C2)	Run (D) 2	0.12421	2.23573	0.89627		**	ns	**
	3	0.17402	2.63249	0.63439		**	ns	**
	4	0.11878	2.35738	0.64138		**	ns	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (C)	Run (D) 2	ns	**	ns				
	3	ns	ns	ns				
	4	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-32. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY RUN (D) BY LEG (E) FOR DISTANCE OFF TRACK FOR 80K TANKER - ANOVA 1

80,000 DWT (A1)		Leg (E)			Interaction	Comparison (E)		
Tug Number (B)		1	2	3	p Value	1-2	1-3	2-3
2 Tugs (B1)	Run (D) 2	0.15158	1.98740	0.68492	0.05	**	ns	**
	3	0.20887	1.71933	0.90825		**	ns	ns
	4	0.23225	1.65595	0.51350		*	ns	*
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
4 Tugs (B2)	Run (D) 2	0.14589	5.10078	1.21879		**	ns	**
	3	0.22132	2.86263	0.37752		**	ns	**
	4	0.18072	2.08710	0.42372		**	ns	**
Comparison (D)	2-3	ns	**	ns				
	2-4	ns	**	ns				
	3-4	ns	ns	ns				
Comparison (B)	Run (D) 2	ns	**	ns				
	3	ns	*	ns				
	4	ns	ns	ns				

** p < 0.01
 * p < 0.05
ns = not significant

TABLE D-33. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY RUN (D) BY LEG (E) FOR DISTANCE OFF TRACK FOR 250K TANKER - ANOVA 1

250,000 DWT (A2) Tug Number (B)		Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
2 Tugs (B1)	Run (D) 2	0.09832	2.14963	0.77153	0.05	**	ns	**
	3	0.22396	1.95825	0.65777		**	ns	**
	4	0.13518	1.76765	0.82271		**	ns	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
4 Tugs (B2)	Run (D) 2	0.19678	2.52570	1.15019		**	ns	**
	3	0.19451	3.68442	0.67979		**	ns	**
	4	0.18453	2.98975	1.22536		**	ns	**
Comparison (D)	2-3	ns	*	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
Comparison (B)	Run (D) 2	ns	ns	ns				
	3	ns	**	ns				
	4	ns	*	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-34. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY RUN (D) BY LEG (E) FOR DISTANCE OFF TRACK - SHIP TYPE (A) COMPARISONS - ANOVA 1

				Legs (E)	
Comparison (A)	Tug Number (B)		1	2	3
		Runs (D) 2	ns	ns	ns
	2 Tugs (B1)	3	ns	ns	ns
		4	ns	ns	ns
		Runs (D) 2	ns	**	ns
	2 Tugs (B2)	3	ns	ns	ns
		4	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-35. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEGS (E) FOR RUDDER CONTRIBUTION - ANOVA 1

Ship Type (A)	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
80,000 DWT	0.13308	0.21378	0.50365	0.01	ns	**	**
250,000 DWT	0.25838	0.45976	0.54340		**	**	ns
Comparison (A)	**	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-36. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY TUG NUMBER (B) FOR TUG CONTRIBUTION
ANOVA 1

Ship Type (A)	Tug Number (B) 2	4	Interaction p Value	Comparison (B)
80,000 DWT	0.00514	0.00458	0.001	ns
250,000 DWT	0.03194	0.05993		**
Comparison (A)	**	**		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-37. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY SHIP TYPE (A) FOR TUG CONTRIBUTION ANOVA 1

	Tug Mode (C)			
Ship Type (A)	Inactive	Active	Interaction p Value	Comparison C
80,000 DWT	0.00103+	0.00869	0.001	ns
250,000 DWT	0.00555+	0.08632		**
Comparison (A)	ns	**		

** p < 0.01
 * p < 0.05
ns = not significant
+ These values should be exactly zero

TABLE D-38. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEGS (E) FOR TUG CONTRIBUTION - ANOVA 1

Ship Type (A)	Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
80,000 DWT	0.00001	0.00079	0.01378	0.001	ns	ns	ns
250,000 DWT	0.00413	0.03027	0.10342		*	**	**
Comparison (A)	ns	**	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-39. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TUG NUMBER (B) FOR TUG CONTRIBUTION ANOVA 1

Tug Number (B)	Tug Mode (C) Inactive	Active	Interaction p Value	Comparison C
2 Tugs	0.00311+	0.03398	0.01	**
4 Tugs	0.00348+	0.06104		**
Comparison (B)	ns	**		

** $p < 0.01$
* $p < 0.05$
ns = not significant
+ These values should be exactly zero

TABLE D-40. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY LEG (E) FOR TUG CONTRIBUTION - ANOVA 1

Tug Mode (C)	Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
Inactive	0.00001 +	0.00000 +	0.00986 +	0.001	ns	ns	ns
Active	0.00413	0.03106	0.10734		*	**	**
Comparison (C)	ns	**	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant
+ These values should be exactly zero

TABLE D-41. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY TUG NUMBER (B) BY TUG MODE (C) FOR TUG CONTRIBUTION - ANOVA 1

	Tug Number (B)		Interaction	
	2 Tugs	4 Tugs	p Value	Comparison (B)
Inactive (C1)				
80,000 DWT	0.00090	0.00117	0.001	ns
250,000 DWT	0.00532	0.00579		ns
Comparison (A)	ns	ns		
Active (C2)				
80,000 DWT	0.00938	0.00800		ns
250,000 DWT	0.05857	0.11408		**
Comparison (A)	**	**		
Comparison (C)				
80,000 DWT	ns	ns		
250,000 DWT	**	**		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-42. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY TUG MODE (C) BY LEG (E) FOR TUG CONTRIBUTION - ANOVA 1

		Leg (E)			Interaction	Comparison (E)		
		1	2	3	p Value	1-2	1-3	2-3
Inactive (C1)								
A	80,000 DWT	0.00000+	0.00000+	0.00310+	0.001	ns	ns	ns
A	250,000 DWT	0.00003+	0.00000+	0.01663+		ns	ns	ns
	Comparison (A)	ns	ns	ns				
Active (C2)								
A	80,000 DWT	0.00003	0.00158	0.02446		ns	ns	ns
A	250,000 DWT	0.00822	0.06053	0.19022		**	**	**
	Comparison (A)	ns	**	**				
Comparison (C)								
	80,000 DWT	ns	ns	ns				
	250,000 DWT	ns	**	**				

** $p < 0.01$ * $p < 0.05$ ns = not significant   + These values should all be zero

TABLE D-43. RELATIONSHIP AMONG MEANS FOR LEGS (E) BY RUNS (D) FOR SWEPT PATH

ANOVA 1

	Leg (E)			Interaction	Comparison (E)		
	1	2	3	p Value	1-2	1-3	2-3
Runs (D)							
2	182.02771	226.11377	249.31860	0.05	**	**	**
3	182.31250	222.91577	228.56824		**	**	ns
4	176.48828	216.25830	228.99426		**	**	*
Comparison (D)							
2-3	ns	ns	**				
2-4	ns	ns	**				
3-4	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-44. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEG (E) FOR SWEPT PATH

ANOVA 1

	Leg (E)			Interaction	Comparison (E)		
Ship Type (A)	1	2	3	p Value	1-2	1-3	2-3
80,000 DWT	154.06143	184.65811	198.88110	0.05	**	**	*
250,000 DWT	206.49080	258.86719	272.37305		**	**	*
Comparison (A)	**	**	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-45. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEG (E) BY TUG MODE (C) FOR SWEPT PATH - ANOVA 1

	Leg (E)			Interaction	Comparison (E)		
Ship Type (A)	1	2	3	p Value	1-2	1-3	2-3
Inactive (C1)							
80,000 DWT	150.84373	192.50049	195.26367	0.01	**	**	ns
250,000 DWT	208.87222	246.99414	279.38135		**	**	**
Comparison (A)	**	**	**				
Active (C2)							
80,000 DWT	157.27922	176.81592	202.49837		ns	**	**
250,000 DWT	204.10953	270.73999	265.36475		**	**	ns
Comparison (A)	**	**	**				
Comparison (C)							
A 80,000 DWT	ns	ns	ns				
A 250,000 DWT	ns	**	ns				

** p < 0.01
* p < 0.05
ns = not significant

TABLE D-46. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEGS (E) FOR MEAN SPEED

ANOVA 1

	Leg (E)			Interaction	Comparison (E)		
Ship Type (A)	1	2	3	p Value	1-2	1-3	2-3
80,000 DWT (A1)	7.57958	5.48866	4.33640	0.001	**	**	**
250,000 DWT (A2)	9.09644	6.79583	4.00621		**	**	**
Comparison (A)	**	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-47. RELATIONSHIP AMONG MEANS FOR LEGS (E) BY RUNS (D) FOR MEAN SPEED

ANOVA 1

	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
Runs (D)							
2	8.14952	5.53096	3.81307	0.01	**	**	**
3	8.33225	6.26256	4.32331		**	**	**
4	8.53227	6.63323	4.37754		**	**	**
Comparison (D)							
2-3	ns	**	**				
2-4	*	**	**				
3-4	ns	**	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-48. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY TUG MODE (C) BY RUNS (D) FOR MEAN SPEED - ANOVA 1

		Runs (D)			Interaction	Comparison (D)		
Ship Type (A)		2	3	4	p Value	2-3	2-4	3-4
Inactive (C1)								
A	80,000 DWT	4.77896	5.94222	6.37632	0.05	**	**	ns
	250,000 DWT	6.80271	6.79911	6.53365		ns	ns	ns
	Comparison (A)	**	**	ns				
Active (C2)								
A	80,000 DWT	5.35241	6.02585	6.33353		*		
	250,000 DWT	6.39065	6.45698	6.81388		ns	ns	ns
	Comparison (A)	**	ns	*				
Comparison (C)								
A	80,000 DWT	*	ns	ns				
	250,000 DWT	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-49. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUNS (D) FOR MEAN SPEED

ANOVA 1

	Runs (D)			Interaction	Comparison (D)		
Ship Type (A)	2	3	4	p Value	2-3	2-4	3-4
80,000 DWT (A1)	5.06568	5.98403	6.35492	0.001	**	**	ns
250,000 DWT (A2)	6.059667	6.62805	6.67376		ns	ns	ns
Comparison (A)	**	**	*				

** p < 0.01
 * p < 0.05
ns = not significant

TABLE D-50. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUNS (D) FOR TIME RUDDER USED - ANOVA 1

	Runs (D)			Interaction	Comparison (D)		
Ship Type (A)	**2**	**3**	**4**	**p Value**	**2-3**	**2-4**	**3-4**
80,000 DWT (A1)	11.06512	9.23194	8.18291	0.05	**	**	ns
250,000 DWT (A2)	8.72056	8.65159	7.99939		ns	ns	ns
Comparison (A)	**	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-51. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEG (E) FOR PERCENTAGE OF TIME LEFT RUDDER - ANOVA 1

Ship Type (A)	Leg (E) 1	2	3	Interaction p Value	Comparison (D) 1-2	1-3	2-3
80,000 DWT (A1)	5.426	8.771	4.470	0.01	ns	ns	ns
250,000 DWT (A2)	4.648	18.239	10.337		**	*	**
Comparison (A)	ns	**	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-52. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY TUG NUMBER (B) BY RUN (D) FOR PERCENTAGE OF TIME RIGHT RUDDER - ANOVA 1

	Runs (D)			Interaction	Comparison (D)		
Tug Number (B)	2	3	4	p Value	2-3	2-4	3-4
80,000 DWT (A1)							
2 Tugs	66.475	64.012	61.811	0.05	ns	ns	ns
4 Tugs	68.994	61.634	57.597		*	**	ns
Comparison (B)	ns	ns	ns				
250,000 DWT (A2)							
2 Tugs	61.091	61.448	53.392		ns	ns	ns
4 Tugs	54.738	59.451	60.940		ns	ns	ns
Comparison (B)	ns	ns	*				
Comparison (A)							
2 Tugs	ns	ns	*				
4 Tugs	**	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-53. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY LEGS (E) FOR PERCENTAGE OF TIME RIGHT RUDDER USED - ANOVA 1

	Leg (E)			Interaction	Comparison (E)		
Ship Type (A)	1	2	3	p Value	1-2	1-3	2-3
80,000 DWT (A1)	60.209	61.921	68.632	0.01	ns	ns	ns
250,000 DWT (A2)	67.673	53.498	54.359		**	**	ns
Comparison (A)	ns	*	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

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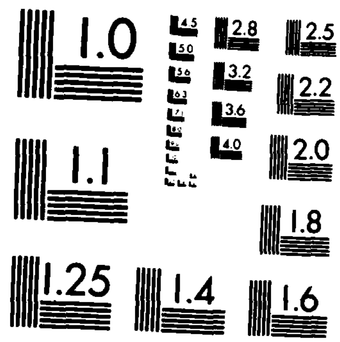

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TABLE D-54. RELATIONSHIP AMONG MEANS FOR HORSEPOWER (H) ANOVA 2

Parameter	4,000 (H)	8,000 (H)	Main Effect p Value
J1	1.71741	1.57040	ns
J2	2.16907	2.00006	ns
J3	2.39898	2.22887	ns
α_1	0.06118	0.06934	ns
α_2	0.51283	0.49898	ns
α_3	0.74276	0.72779	ns
Distance Off Track Contribution	1.18978	1.08189	ns
Rudder Contribution	0.42051	0.40412	ns
Tug Moment Contribution	0.04594	0.01507	0.001
Percentage Time Left Rudder	11.075	12.336	ns
Percentage Time Right Rudder	58.510	55.391	ns
Time Rudder Used in Leg (min.)	8.45718	8.65784	ns
Swept Path (ft)	245.91028	247.13910	ns
Mean Speed (ft/sec.)	6.63283	6.38685	ns

TABLE D-55. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) ANOVA 2

Parameter	2 Tugs (B1)	4 Tugs (B2)	Main Effect p Value
J1	1.48769	1.80014	ns
J2	1.94588	2.22324	ns
J3	2.16950	2.45836	ns
α_1	0.06300	0.06752	ns
α_2	0.52119	0.49062	ns
α_3	0.74481	0.72574	ns
Distance Off Track Contribution	1.00927	1.26240	ns
Rudder Contribution	0.38883	0.43581	ns
Tug Moment Contribution	0.02660	0.03441	ns
Percentage Time Left Rudder	11.705	11.706	ns
Percentage Time Right Rudder	56.266	57.636	ns
Time Rudder Used in Leg (min.)	8.59346	8.52156	ns
Swept Path (ft)	243.87866	249.17081	ns
Mean Speed (ft/sec.)	6.54773	6.47194	ns

TABLE D-56. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) ANOVA 2

Parameter	Inactive (C1)	Active (C2)	Main Effect p Value
J1	1.65122	1.63661	ns
J2	2.08825	2.08088	ns
J3	2.30282	2.32504	ns
α_1	0.06676	0.06375	ns
α_2	0.50379	0.50802	ns
α_3	0.71837	0.75218	ns
Distance Off Track Contribution	1.13127	1.14040	ns
Rudder Contribution	0.44965	0.37499	ns
Tug Moment Contribution	0.00354	0.05746	0.001
Percentage Time Left Rudder	13.343	10.068	ns
Percentage Time Right Rudder	58.121	55.780	ns
Time Rudder Used in Leg (min.)	8.94113	8.17389	ns
Swept Path (ft)	245.14629	247.90318	ns
Mean Speed (ft/sec.)	6.51579	6.50389	ns

TABLE D-57. RELATIONSHIP AMONG MEANS FOR RUNS (D) - ANOVA 2

Parameter	Runs Number (D) 2	3	4	Main Effect p Value	Comparison (D) 2-3	2-4	3-4
J1	1.69019	1.66142	1.58014	ns	--	--	--
J2	2.12209	2.09916	2.03244	ns	--	--	--
J3	2.35488	2.31845	2.26846	ns	--	--	--
α_1	0.06823	0.06320	0.06435	ns	--	--	--
α_2	0.50013	0.50094	0.51665	ns	--	--	--
α_3	0.73292	0.72023	0.75267	ns	--	--	--
Distance Off Track Contribution	1.15307	1.14386	1.11058	ns	--	--	--
Rudder Contribution	0.43857	0.42163	0.37375	*	ns	*	ns
Tug Moment Contribution	0.03032	0.03273	0.02845	ns	--	--	--
Percentage Time Left Rudder	13.006	10.543	11.567	ns	--	--	--
Percentage Time Right Rudder	56.455	59.458	54.940	ns	--	--	--
Time Rudder Used in Leg (min.)	8.95052	8.76750	7.95451	*	ns	*	ns
Swept Path (ft)	252.01822	246.17928	241.37666	*	ns	*	ns
Mean Speed (ft/sec.)	6.38523	6.50061	6.64368	ns	--	--	--

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-58. RELATIONSHIP AMONG MEANS FOR LEGS (E) - ANOVA 2

Parameter	LEG (E) 2	3	4	Main Effect p Value	Comparison (E) 1-2	1-3	2-3
J1	0.46248	2.82970	1.63957	0.001	**	**	**
J2	1.04550	3.49479	1.71341	0.001	**	*	**
J3	1.44758	3.59822	1.89600	0.001	**	ns	**
α_1	0.01490	0.17470	0.00617	0.001	**	ns	**
α_2	0.59792	0.83979	0.08002	0.001	**	**	**
α_3	1.00000	0.94322	0.26260	0.001	**	**	**
Distance Off Track Contribution	0.17897	2.19109	1.03745	0.001	**	**	**
Rudder Contribution	0.26638	0.44612	0.52445	0.001	**	**	*
Tug Moment Contribution	0.00224	0.01778	0.07149	0.001	**	**	**
Percentage Time Left Rudder	5.446	18.024	11.647	0.001	**	**	**
Percentage Time Right Rudder	64.833	53.065	52.955	0.001	**	**	ns
Time Rudder Used in Leg (min.)	6.52161	7.80606	11.34486	0.001	*	**	**
Swept Path (ft)	212.15723	255.98753	271.47949	0.001	**	**	**
Mean Speed (ft/sec.)	8.98740	6.58764	3.95448	0.001	**	**	**

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-59. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) BY LEG (E) FOR J1 - ANOVA 2

	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
INACTIVE (C1)							
4,000 (H1)							
2 Tugs	0.35690	1.90107	1.50340	0.05	*	ns	ns
4 Tugs	0.59919	4.08053	1.50117		**	ns	**
Comparison (B)	ns	**	ns				
8,000 (H2)							
2 Tugs	0.45644	2.49265	1.49943		**	ns	ns
4 Tugs	0.63939	2.34496	2.43950		*	*	ns
Comparison (B)	ns	ns	ns				
ACTIVE (C2)							
4,000 (H1)							
2 Tugs	0.38285	3.20023	1.27349		**	ns	**
4 Tugs	0.43142	3.50840	1.87024		**	ns	*
Comparison (B)	ns	ns	ns				
8,000 (H2)							
2 Tugs	0.50838	2.30631	1.97110		*	ns	ns
4 Tugs	0.32525	2.80341	1.05818		**	ns	**
Comparison (B)	ns	ns	ns				

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COMPARISON (H)

		E1	E2	E3
C_1	B1	ns	ns	ns
	B2	ns	*	ns
C_2	B1	ns	ns	ns
	B2	ns	ns	ns

COMPARISON (C)

		E1	E2	E3
H_1	B1	ns	*	ns
	B2	ns	ns	ns
H_2	B1	ns	ns	ns
	B2	ns	ns	*

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-60. RELATIONSHIP AMONG MEANS FOR RUNS (D) BY TUG NUMBER (B) BY HORSEPOWER (H) FOR α_2 - ANOVA 2

Tugs Number (B)	Run (D) 2	Run (D) 3	Run (D) 4	Interaction p Value	Comparison (D) 2-3	Comparison (D) 2-4	Comparison (D) 3-4
4,000 (H1)							
2 Tugs	0.50959	0.53759	0.53039	0.05	ns	ns	ns
4 Tugs	0.52084	0.47942	0.49916		ns	ns	ns
Comparison B	ns	ns	ns				
8,000 (H2)							
2 Tugs	0.52849	0.47706	0.54402		ns	ns	ns
4 Tugs	0.44161	0.50969	0.49303		ns	ns	ns
Comparison B	*	ns	ns				
Comparison (H)							
2 Tugs	ns	ns	ns				
4 Tugs	*	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-61. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TUG NUMBER (B) BY LEG (E) FOR α_2 - ANOVA 2

	Leg (E)			Interaction	Comparison (E)		
Tugs Number (B)	1	2	3	p Value	1-2	1-3	2-3
Inactive (C1)							
2 Tugs	0.63810	0.89708	0.05729	0.05	**	**	**
4 Tugs	0.56692	0.79247	0.07089		**	**	**
Comparison B	ns	*	ns				
Active (C2)							
2 Tugs	0.59974	0.80073	0.13420		**	**	**
4 Tugs	0.58690	0.86887	0.05769		**	**	**
Comparison B	ns	ns	ns				
Comparison (C)							
2 Tugs	ns	ns	ns				
4 Tugs	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-62. RELATIONSHIP AMONG MEANS FOR HORSEPOWER (H) BY TUG NUMBER (B) FOR α_3 - ANOVA 2

Horsepower (H)	Tugs Number (B) 2 Tugs	4 Tugs	Interaction p Value	Comparison B
4,000	0.72501	0.76050	0.01	ns
8,000	0.76461	0.69098		**
Comparison (H)	ns	**		

** p < 0.01
 * p < 0.05
ns = not significant

TABLE D-63. RELATIONSHIP AMONG MEANS FOR HORSEPOWER (H) BY LEGS (E) BY TUG NUMBER (B) FOR α_3 - ANOVA 2

	Leg (E)			Interaction	Comparison (E)		
Tug Number (B)	1	2	3	p Value	1-2	1-3	2-3
4,000 (H1)							
2 Tugs	1.00000	0.94554	0.22950	0.01	ns	**	**
4 Tugs	1.00000	0.94140	0.34011		ns	**	**
Comparison B	ns	ns	*				
8,000 (H2)							
2 Tugs	1.00000	0.95116	0.34266		ns	**	**
4 Tugs	1.00000	0.93480	0.13814		ns	**	**
Comparison B	ns	ns	**				
Comparison (H)							
2 Tugs	ns	ns	*				
4 Tugs	ns	ns	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-64. RELATIONSHIP AMONG MEANS FOR HORSEPOWER (H) BY LEGS (E) FOR TUG CONTRIBUTION - ANOVA 2

	Leg (E)			Interaction	Comparison (E)		
Horsepower (H)	1	2	3	p Value	1-2	1-3	2-3
4,000	0.00413	0.03027	0.10342	0.01	*	**	**
8,000	0.00034	0.00529	0.03956		ns	**	**
Comparison (H)	ns	*	**				

** $p < 0.01$
 * $p < 0.05$
ns = not significant

TABLE D-65. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY LEG (E) FOR TUG CONTRIBUTION - ANOVA 2

	Leg (E)			Interaction	Comparison (E)		
Tug Mode (C)	1	2	3	p Value	1-2	1-3	2-3
Inactive	0.00007+	0.00006+	0.01050+	0.001	ns	ns	ns
Active	0.00440	0.03550	0.13249		*	**	**
Comparison (C)	ns	**	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant
+ These values should be exactly zero

TABLE D-66. RELATIONSHIP AMONG MEANS FOR HORSEPOWER (H) BY TUG NUMBER (B) FOR TUG CONTRIBUTION - ANOVA 2

Horsepower (H)	Tug Number (B) 2 Tugs	Tug Number (B) 4 Tugs	Interaction p Value	Comparison (B)
4,000	0.03194	0.05993	0.001	**
8,000	0.02125	0.00888		ns
Comparison (H)	ns	**		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-67. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) FOR TUG CONTRIBUTION - ANOVA 2

Tug Mode (C)	Horsepower (H) 4,000	Horsepower (H) 8,000	Interaction p Value	Comparison (H)
Inactive	0.00555+	0.00154+	0.001	ns
Active	0.08632	0.02860		**
Comparison (C)	**	**		

** $p < 0.01$
 * $p < 0.05$
ns = not significant
+ These values should be exactly zero

TABLE D-68. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) FOR TUG CONTRIBUTION ANOVA 2

Horsepower (H)	Tug Number (B) 2 Tugs	4 Tugs	Interaction p Value	Comparison (B)
Inactive (C1)				
4,000	0.00532+	0.00579+	0.001	ns
8,000	0.00180+	0.00127+		ns
Comparison (H)	ns	ns		
Active (C2)				
4,000	0.05857	0.11408		**
8,000	0.04070	0.01649		**
Comparison (H)	ns	**		
Comparison (C)				
4,000	**	**		
8,000	**	ns		

** $p < 0.01$
* $p < 0.05$
ns = not significant
+ These values should be exactly zero

TABLE D-69. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY LEG (E) FOR TUG CONTRIBUTION - ANOVA 2

Horsepower (H)	Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
Inactive (C1)							
4,000	0.00003+	0.00000+	0.01663+	0.01	ns	ns	ns
8,000	0.00012+	0.00012+	0.00437+		ns	ns	ns
Comparison (H)	ns	ns	ns				
Active (C2)							
4,000	0.00822	0.06053	0.19022		**	**	**
8,000	0.00057	0.01046	0.07476		ns	**	**
Comparison (H)	ns	**	**				
Comparison (C)							
4,000	ns	**	**				
8,000	ns	ns	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant
+ These values should be exactly zero

TABLE D-70. RELATIONSHIP AMONG MEANS FOR HORSEPOWER (H) BY LEGS (E) BY TUG NUMBER (B) FOR TUG CONTRIBUTION - ANOVA 2

	Leg (E)			Interaction	Comparison (E)		
Tugs Number (B)	1	2	3	p Value	1-2	1-3	2-3
4,000 (H1)							
2 Tugs	0.00017	0.02054	0.07512	0.05	ns	**	**
4 Tugs	0.00808	0.04000	0.13173		ns	**	**
Comparison B	ns	ns	**				
8,000 (H2)							
2 Tugs	0.00056	0.00872	0.05447		ns	**	**
4 Tugs	0.00013	0.00186	0.02466		ns	ns	ns
Comparison B	ns	ns	*				
Comparison (H)							
2 Tugs	ns	ns	ns				
4 Tugs	ns	*	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-71. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) BY LEG (E) FOR TUG CONTRIBUTION - ANOVA 2

	Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
INACTIVE (C1)							
4,000 (H1)							
2 Tugs	0.00005+	0.00000+	0.01589+	0.05	ns	ns	ns
4 Tugs	0.00000+	0.00000+	0.01736+		ns	ns	ns
Comparison (B)	ns	ns	ns				
8,000 (H2)							
2 Tugs	0.00000+	0.00000+	0.00539+		ns	ns	ns
4 Tugs	0.00024+	0.00023+	0.00334+		ns	ns	ns
Comparison (B)	ns	ns	ns				
ACTIVE (C2)							
4,000 (H1)							
2 Tugs	0.00029	0.04108	0.13434		ns	**	**
4 Tugs	0.01615	0.07999	0.24609		*	**	**
Comparison (B)	ns	ns	*				
8,000 (H2)							
2 Tugs	0.00111	0.01744	0.10355		ns	**	**
4 Tugs	0.00002	0.00348	0.04597		ns	ns	*
Comparison (B)	ns	ns	**				

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COMPARISON (H)

		E1	E2	E3
C_1	B1	ns	ns	ns
	B2	ns	ns	ns
C_1	B1	ns	ns	ns
	B2	ns	**	**

COMPARISON (C)

		E1	E2	E3
H_1	B1	ns	ns	**
	B2	ns	**	**
H_2	B1	ns	ns	**
	B2	ns	ns	*

** $p < 0.01$ * $p < 0.05$ ns = not significant   + These values should all be zero

TABLE D-72. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) BY LEG (E) FOR SWEPT PATH - ANOVA 2

Tugs Number (B)	Leg (E) 1	2	3	Interaction p Value	Comparison (E) 1-2	1-3	2-3
C1 H1							
2 Tugs	212.94232	233.56087	265.99414	0.05	ns	**	*
4 Tugs	204.80238	260.42725	292.76855		**	**	*
Comparison B	ns	ns	ns				
C1 H2							
2 Tugs	210.45044	260.62207	241.50113		**	ns	ns
4 Tugs	224.38045	241.71584	292.58984		ns	**	**
Comparison B	ns	ns	**				
C2 H1							
2 Tugs	194.25598	271.55493	262.02002		**	**	ns
4 Tugs	213.96362	269.92480	268.70947		**	**	ns
Comparison B	ns	ns	ns				
C2 H2							
2 Tugs	225.91888	257.32080	290.40210		ns	**	*
4 Tugs	210.54459	252.37210	257.85083		*	**	ns
Comparison B	ns	ns	ns				

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COMPARISON (C)			E1	E2	E3
	H1	B1	ns	*	ns
		B2	ns	ns	ns
	H2	B1	ns	ns	**
		B2	ns	ns	*

COMPARISON (H)			E1	E2	E3
	C2	B1	ns	ns	ns
		B2	ns	ns	ns
	C2	B1	*	ns	ns
		B2	ns	ns	ns

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-73. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TUG NUMBER (B) BY LEG (E) FOR SWEPT PATH - ANOVA 2

	Leg (E)			Interaction	Comparison (E)		
Tugs Number (B)	1	2	3	p Value	1-2	1-3	2-3
Inactive (C1)							
2 Tugs	211.69644	247.09146	253.74771	0.05	**	**	ns
4 Tugs	214.59131	251.07178	292.67896		**	**	**
Comparison B	ns	ns	**				
Active (C2)							
2 Tugs	210.08740	264.43774	276.21118		**	**	ns
4 Tugs	212.25423	261.14819	263.28003		**	**	ns
Comparison B	ns	ns	ns				
Comparison (C)							
2 Tugs	ns	ns	*				
4 Tugs	ns	ns	**				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-74. RELATIONSHIP AMONG MEANS FOR LEGS (E) BY RUNS (D) FOR SWEPT PATH

ANOVA 2

	Leg (E)			Interaction	Comparison (E)		
	1	2	3	p Value	1-2	1-3	2-3
Runs (D)							
2	217.18298	254.43799	284.43359	0.05	**	**	**
3	211.09387	259.56421	267.87939		**	**	ns
4	208.19495	253.80981	262.12549		**	**	ns
Comparison (D)							
2-3	ns	ns	**				
2-4	ns	ns	**				
3-4	ns	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-75. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY TUG NUMBER (B) FOR SWEPT PATH - ANOVA 2

Tug Mode (C)	Tug Number (B) 2 Tugs	4 Tugs	Interaction p Value	Comparison (B)
Inactive	237.51193	252.78076	0.05	*
Active	250.24548	245.56076		ns
Comparison (C)	ns	ns		

** p < 0.01
 * p < 0.05
ns = not significant

TABLE D-76. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY LEGS (E) BY RUNS (D) FOR MEAN SPEED - ANOVA 2

250,000 DWT (A2)		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
C1 H1	Run (D) 2	9.20521	7.01682	4.18609	0.05	**	**	**
	3	9.08425	6.81943	4.49365		**	**	**
	4	9.08105	6.71407	3.80584		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	**				
C1 H2	Run (D) 2	8.78938	6.04128	2.94664		**	**	**
	3	8.90170	6.39338	3.96325		**	**	**
	4	8.96315	6.65928	4.21982		**	**	**
Comparison (D)	2-3	ns	ns	**				
	2-4	ns	**	**				
	3-4	ns	ns	ns				
C2 H1	Run (D) 2	8.99719	6.39006	3.78470		**	**	**
	3	9.01846	6.71601	3.63647		**	**	**
	4	9.19253	7.11862	4.13049		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	**	ns				
	3-4	ns	*	*				
C2 H2	Run (D) 2	8.81088	6.29402	4.16043		**	**	**
	3	8.76239	6.24508	3.97330		**	**	**
	4	9.04268	6.64361	4.15314		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-77. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY LEGS (E) BY RUNS (D) FOR MEAN SPEED - ANOVA 2 (CONTINUED)

Comparison (C)			Legs (E)		
			1	2	3
H1	Run (D)	2	ns	**	*
		3	ns	ns	**
		4	ns	*	ns
H2	Runs (D)	2	ns	ns	*
		3	ns	ns	ns
		4	ns	ns	ns

Comparison (H)			Legs (E)		
			1	2	3
C1	Run (D)	2	*	**	**
		3	ns	*	*
		4	ns	ns	**
C2	Run (D)	2	ns	ns	ns
		3	ns	*	ns
		4	ns	*	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-78. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) FOR MEAN SPEED ANOVA 2

Horsepower (H)	Tug Number (B) 2 Tugs	4 Tugs	Interaction p Value	Comparison (B)
Inactive				
2,000	6.52811	6.89554	0.01	ns
4,000	6.97283	5.66670		**
Comparison (H)	ns	**		
Active (C2)				
2,000	6.80385	6.30382		ns
4,000	5.88615	7.02174		*
Comparison (H)	*	ns		
Comparison (C)				
2,000	ns	ns		
4,000	*	**		

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-79. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY RUNS (D) FOR MEAN SPEED - ANOVA 2

	Run Number (D)			Interaction	Comparison (D)		
	2	3	4	p Value	2-3	2-4	3-4
Inactive (C1)							
4,000	6.80271	6.79911	6.53365	0.05	ns	ns	ns
8,000	5.92576	6.41944	6.61409		ns	**	ns
Comparison (H)	**	ns	ns				
Active (C2)							
4,000	6.39065	6.45698	6.81388		ns	ns	ns
8,000	6.42178	6.32692	6.61314		ns	ns	ns
Comparison (H)	ns	ns	ns				
Comparison (C)							
H1	ns	ns	ns				
H2	*	ns	ns				

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-80. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) BY LEG (E) BY RUN (D) FOR MEAN SPEED - ANOVA 2

Inactive Mode (C1)		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
H1 B1	Run (D) 2	9.27992	6.86650	3.86086	0.05	**	**	**
	3	8.99072	6.48876	4.48777		**	**	**
	4	8.93618	6.22561	3.61668		**	**	**
Comparison (D)	2-3	ns	ns	*				
	2-4	ns	ns	ns				
	3-4	ns	ns	*				
H1 B2	Run (D) 2	9.13051	7.16714	4.51133		**	**	**
	3	9.17778	7.15011	4.49953		**	**	**
	4	9.22591	7.20253	3.99499		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
H2 B1	Run (D) 2	9.44407	7.21393	3.54998		**	**	**
	3	9.38784	7.24877	3.97026		**	**	**
	4	9.63364	7.78198	4.52497		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	**				
	3-4	ns	ns	ns				
H2 B2	Run (D) 2	8.13468	4.86863	2.34330		**	**	**
	3	8.41557	5.53798	3.95624		**	**	**
	4	8.29266	5.53659	3.91467		**	**	**
Comparison (D)	2-3	ns	ns	**				
	2-4	ns	ns	**				
	3-4	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-81. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) BY LEG (E) BY RUN (D) FOR MEAN SPEED - ANOVA 2 (CONTINUED)

Active Mode (C2)		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
H1 B1	Run (D) 2	8.99559	6.47445	4.10488	0.05	**	**	**
	3	9.15024	6.98678	3.73324		**	**	**
	4	9.45203	7.63358	4.70389		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	**	*				
	3-4	ns	*	**				
H1 B2	Run (D) 2	8.99879	6.30567	3.46452		**	**	**
	3	8.88668	6.44523	3.53969		**	**	**
	4	8.93303	6.60367	3.55709		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
H2 B1	Run (D) 2	8.57049	5.46976	3.34278		**	**	**
	3	8.34667	5.33458	3.34739		**	**	**
	4	8.61292	6.09019	3.86061		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	*	ns				
	3-4	ns	*	ns				
H2 B2	Run (D) 2	9.05127	7.11828	4.97808		**	**	**
	3	9.17810	7.15557	4.59920		**	**	**
	4	9.47244	7.19703	4.44567		**	**	**
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-82. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY TUG NUMBER (B) BY LEG (E) BY RUN (D) FOR MEAN SPEED - ANOVA 2 (CONTINUED)

Comparison (H)

		Leg (E) 1	2	3
C1 B1	Runs (D) 2	ns	ns	ns
	3	ns	*	ns
	4	*	**	**
C1 B2	Runs (D) 2	**	**	**
	3	*	**	ns
	4	**	**	ns
C2 B1	Runs (D) 2	ns	**	*
	3	**	**	ns
	4	**	**	**
C2 B2	Runs (D) 2	ns	**	**
	3	ns	*	**
	4	ns	*	**

Comparison (B)

		Leg (E) 1	2	3
C1 H2	Runs (D) 2	ns	ns	*
	3	ns	*	ns
	4	ns	*	ns
C1 H2	Runs (D) 2	**	**	**
	3	**	**	ns
	4	**	**	*
C2 H1	Runs (D) 2	ns	ns	*
	3	ns	ns	ns
	4	ns	**	**
C2 H2	Runs (D) 2	ns	**	**
	3	*	**	**
	4	*	**	*

Comparison (C)

		Leg (E) 1	2	3
H1 B1	Runs (D) 2	ns	ns	ns
	3	ns	ns	*
	4	ns	**	**
H1 B2	Runs (D) 2	ns	**	**
	3	ns	*	**
	4	ns	*	ns
H2 B1	Runs (D) 2	**	**	ns
	3	**	**	*
	4	**	**	*
H2 B2	Runs (D) 2	**	**	**
	3	**	**	*
	4	**	**	ns

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-83. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY LEGS (E) BY RUNS (D) FOR PERCENTAGE OF TIME RIGHT RUDDER - ANOVA 2

		Leg (E) 1	Leg (E) 2	Leg (E) 3	Interaction p Value	Comparison (E) 1-2	Comparison (E) 1-3	Comparison (E) 2-3
C1 H1	Run (D) 2	0.66761	0.53032	0.60786		ns	ns	ns
	3	0.65733	0.56272	0.64964		ns	ns	ns
	4	0.72541	0.53834	0.56531		**	**	ns
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
C1 H2	Run (D) 2	0.59947	0.55895	0.43528		ns	*	ns
	3	0.66261	0.49143	0.58973		*	ns	ns
	4	0.60876	0.46940	0.54167		ns	ns	ns
Comparison (D)	2-3	ns	ns	*				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
C2 H1	Run (D) 2	0.63855	0.58479	0.44575		ns	**	*
	3	0.67707	0.52997	0.55025		*	*	ns
	4	0.69443	0.46375	0.44274		**	**	ns
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				
C2 H2	Run (D) 2	0.58378	0.55[illegible]10	0.56912		ns	ns	ns
	3	0.68444	0.57[illegible]92	0.50584		ns	*	ns
	4	0.58047	0.5[illegible]109	0.45139		ns	ns	ns
Comparison (D)	2-3	ns	ns	ns				
	2-4	ns	ns	ns				
	3-4	ns	ns	ns				

** $p < 0.01$ * $p < 0.05$ ns = not significant

TABLE D-84. RELATIONSHIP AMONG MEANS FOR TUG MODE (C) BY HORSEPOWER (H) BY LEGS (E) BY RUNS (D) FOR PERCENTAGE OF TIME RIGHT RUDDER - ANOVA 2 (CONTINUED)

Comparison (C)

			Legs (E) 1	2	3
H1	Run (D)	2	ns	ns	**
		3	ns	ns	ns
		4	ns	ns	*
H2	Runs (D)	2	ns	ns	*
		3	ns	ns	ns
		4	ns	ns	ns

Comparison (H)

			Legs (E) 1	2	3
C1	Run (D)	2	ns	ns	**
		3	ns	ns	ns
		4	ns	ns	ns
C2	Run (D)	2	ns	ns	*
		3	ns	ns	ns
		4	ns	ns	ns

** $p < 0.01$
* $p < 0.05$
ns = not significant

TABLE D-85. RELATIONSHIP AMONG MEANS FOR TUG NUMBER (B) BY RUN (D) FOR PERCENTAGE OF TIME RIGHT RUDDER - ANOVA 2

Tug Number (B)	Leg (E) 2	3	4	Interaction p Value	Comparison (E) 2-3	2-4	3-4
2 Tugs	58.089	59.428	51.280	0.05	ns	*	*
4 Tugs	54.820	59.488	58.599		ns	ns	ns
Comparison (B)	ns	ns	**				

** p < 0.01
* p < 0.05
ns = not significant

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